Incorporating Human Factors into Process Plant Lifecycle: HF during Design and Operation of a Process Plant

Von der Fakultät für Machinenbau, Verfahrens- und Energietechnik
der Technischen Universität Bergakademie Freiberg

genehmigte

DISSERTATION

zur Erlangung des akademischen Grades

Doktor der Ingenieurwissenschaften
Dr.-Ing.

vorgelegt

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geboren am 5. Juli 1981 in Jakarta, Indonesien

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Tag der Verleihung: 10. Juni 2011

There will be no giant leap without a small step...

ACKNOWLEDGEMENT

The completion of this work would have not been achievable without the contribution of many parts and important people in my life. On this first page I would like to express my appreciation and acknowledge all support I have received during this work.

First I would like to express my appreciation to Prof. Dr.-Ing. habil. Jens-Uwe Repke for taking the position of the first supervisor of this work. His valuable contribution and advice have helped the completion of this work.

I would like to extend my gratitude to Prof. Dr.-Ing. habil. Katharina Löwe for her supervision, support and advices from even prior to the beginning of this work. Her expertise and valuable inputs have assisted this work to come to conclusion.

My gratitude goes also to Prof. Dr.-Ing. Dimosthenis Trimis for taking the position of the leader of the examination commission and to Prof. Dr.-Ing. Matthias Kröger as the third reviewer of this work.

For the opportunity to conduct industrial observations, investigations and surveys I would like to thank Bayer CropScience AG, in Frankfurt am Main, Germany. To Dr. Heinz-Josef Löher, Lars Grunenberg, Dr. Wilfried Schmieder and the entire management and co-workers, I dedicate my appreciation for helping and facilitating me during different visits at their plants. Their open arms and thoughtfulness have given significant contribution to this work.

To all my former colleagues in the Department of Plant and Process Safety at TU Berlin, and to the leader of the Department, Prof. Dr.-Ing. Jörg Steinbach, I would like to express my gratitude for giving me a golden opportunity to be a part of their team. My time with them has brought a significant and positive impact to my life and had provided me with invaluable experiences.

My greatest gratitude goes to my beloved parents for their unconditional love and support in every step I have been taking. I dedicate my utmost gratefulness to my beloved husband, who has been tireless encouraging me, for his love and understanding through all the worries and difficulties. I would also like to express my gratitude to my wonderful brother, who has always been giving his priceless advices during this work and in this life, also to my beloved mother-in-law for caring and understanding me all this time. To all my dearest friends in Indonesia and Germany, or wherever they are, I would like to express my appreciation for giving me their wonderful friendship and bringing the excitement into this life.

Above of all, I praise Allah SWT. for the life I have been living, for the invaluable moments I have experienced and for giving me so many precious people to love in this life.

ABSTRACT

Major accidents in the process industries occurred mostly as an outcome of multiple failures in different safety barriers and their interrelation with unsafe acts by frontline operators. This has become the reason why safety analyses in terms of plant technical aspects cannot be performed independently from analysing human response to the changing technology. Unsafe acts and errors by operators must be seen as a symptom of system insufficiencies and underlying problems, rather than as the cause of an accident. With this paradigm, the need to optimally configure the system and the whole working condition to understand human's limitation and requirements becomes very evident. It is too naive to desire that human operators make zero error by asking them to change their behaviour and to perfectly adapt to the system.

Human Factors (HF) attempts to cope with the need to understand the interrelation between human operators, the technology they are working with and the management system, with the aim to increase safety and efficiency. In achieving this goal, HF must be incorporated into the whole plant lifecycle, from the earliest design stage to plant operation and modifications. Moreover, HF analysis must comprise all kinds of operators' activities and responsibilities in operating process plants, which can include manual works in field and supervisory control conducted remotely from a control centre/room.

This work has developed techniques that provide systematic way to incorporate HF into process plant lifecycle. The new HF analysis technique, *PITOPA-Design*, in a combination with the classic PITOPA, is applicable for an implementation during design and operation of a plant. With the awareness that safety analysis and HF cannot be performed separately, an interconnection with HAZOPs is made possible by means of this new technique. Moreover, to provide a systematic analysis of operators' work in control room, an additional technique, the *PITOPA-CR* was also developed. This HF technique can as well be integrated into a general HF analysis both during design phase and plant operation. In addition to it, results coming from *PITOPA-CR* will provide information required to optimally configure control and alarm system, as well as the whole alarm management system to better understand the limitation and requirements of control room operators.

The structure of the development can be described as follows:

i) Development of *HAZOPA* (the Hazards and Operator Actions Analysis), which provides the interconnection between HF analysis and HAZOPs,

ii) Development of *PITOPA-Design*, a technique to incorporate HF consideration into design phase, which is differentiated into 3 stages to comprise the conceptual design, the basic engineering and the detail engineering phase,

iii) Development of *PITOPA-CR*, a technique for HF analysis in control room,

iv) Integration of *PITOPA-CR* into alarm management system, development of a technique for alarm prioritization.

ZUSAMMENFASSUNG

Schwere Unfälle in der Prozessindustrie erfolgen meist aus einem Zusammenspiel mehrerer verschiedener Fehler und der gleichzeitigen Wechselwirkung mit falschem menschlichem Handeln. Dabei sind diese Fehlhandlungen nicht als Unfallursache anzusehen, sondern sie resultieren aus Fehlern, die in dem System selbst zu finden sind. Aus diesem Grund kann bei der Sicherheitsanalyse die technische Analyse nicht unabhängig von der Betrachtung des Human Factors (HF) durchgeführt werden. Um eine Reduzierung der Fehlhandlungen zu erreichen, müssen das Anlagendesign, die Bedienbarkeit und die Arbeitsumgebung an die menschlichen Fähigkeiten angepasst werden.

Human Factors (HF) betrachtet die Interaktion zwischen menschlichen, technischen und organisatorischen Aspekten einer Anlage, mit dem Ziel die Sicherheit und Effektivität der Anlage zu optimieren. Dafür ist eine Einbindung von HF in den gesamten Lebenszyklus einer Anlage notwendig. So müssen HF- Analysen nicht nur während des Betriebs einer Anlage und bei Prozessmodifikationen durchgeführt werden, sondern auch während des gesamten Design-Prozesses, da gerade in den frühen Design-Phasen das Optimierungspotential besonders hoch ist. Eine solche Analysemethode muss alle Aufgaben eines Operators erfassen, so dass zwischen manueller Arbeit und der Arbeit in der Leitwarte unterschieden werden muss.

In dieser Arbeit wurden Analysentechniken entwickelt, die einen systematischen Ansatz zur Berücksichtigung des HF über den gesamten Lebenszyklus einer verfahrenstechnischen Anlage darstellen. Mit Hilfe der neuen Analysemethode, PITOPA-Design, können Untersuchungen sowohl während der Designphase als auch während des Betriebs einer Anlage durchgeführt werden. Da solche HF-Analyse immer in Verbindung mit einer klassischen Sicherheitsanalyse erfolgen muss, bindet die neue Methode die HAZOP-Analyse direkt ein.

Darüber hinaus wurde ein weiterer Ansatz für die Analyse von Operatorhandlungen in einer Messwartenarbeit entwickelt. Diese neue Analysentechnik, PITOPA-CR, bildet die Grundlage für Verbesserungen im Alarmsystem und wird in das Alarmmanagementsystem eingebunden.

Die Arbeit ist wie folgt strukturiert:

- *i) Entwicklung von HAZOPA (the Hazards and Operator Actions Analysis). Diese Methode stellt die Einbindung der HF-Analyse in HAZOP dar.*
- *ii) Entwicklung von PITOPA-Design, zur HF-Analyse während des gesamten Designprozesses einer verfahrenstechnischen Anlage. Die Methode wurde in 3 Teile eingeteilt, um die drei Designsphasen Conceptual-, Basic-, und Detail-Design zu erfassen.*
- *iii) Entwicklung von PITOPA-CR, zur HF-Analyse in der Messwarte.*
- *iv) Einbindung von PITOPA-CR in das Alarmmanagementsystem und Entwicklung einer Technik zur Alarmpriorisierung.*

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NOMENCLATURE

CI	Consistency Index
CR	Consistency Ratio
d	Distance between two instances
k	Number of training examples
PA_n	Priority of a query alarm An
PF	Priority Factor
RI	Random Consistency Index
λ_{max}	Biggest eigenvalue of a pair-wise comparison matrix

ACRONYMS AND ABBREVIATIONS

AHP	Analytical Hierarchy Process
CBP	Computer Based Operating Procedure System Human Factors
CPQRA	Chemical Process Quantitative Risk Analysis
CROAA	Control Room Operator Actions Analysis
CR-PIFs	Control Room Performance Influencing Factors
CRTA	Control Room Task Analysis
DCS	Distributed control system
ERP	Emergency response procedures
ESD	Emergency shutdown system
ETA	Event Tree Analysis
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
GEMS	Generic Error-Modelling System
GOMS	Goal, Operators, Methods and Selection Rules
HAZOPA	Hazard, Operability and Operator Action Analysis
HAZOPs	Hazard and Operability study
HEP	Human error probability
HF	Human Factors
HFAD	Human Factors Analysis in Design
HFD-catalogues	Human factors design catalogues
HMI	Human-machine interface
HRA	Human Reliability Analysis
HSI	Human-system interface
HTA	Hierarchical Task Analysis
ISD	Inherently safer design
kNN	k-Nearest Neighbor
MCDM	Multi-Criteria Decision Making
MOC	Management of change
OAA	Operator Actions Analysis
OSS	Operator supporting system
P&IDs	Piping and instrumentation diagrams
PIF(s)	Performance influencing factor(s)

PITOPA	Process Industry Tool for Operator Action Analysis
SA	Situational awareness
SAPAT	Situational Awareness Process Analysis Technique
SRK	Skill-, rule- and knowledge based
TA	Task Analysis
THERP	Technique for Human Error Rate Prediction
VDU	Visual display unit

CHAPTER 1

INTRODUCTION

1.1 Background

Over the past decades, safety control in the process industries has advanced to an established application. For the improvement of safety systems, diverse analysis techniques have been developed and are widely implemented to systematically analyze process installations and to identify potential hazards. However, catastrophic accidents with numerous fatalities, severe injuries and serious damage on facilities still happen on an almost daily basis (Knegtering, et al., 2009). In finding the reason why accidents still happen after such an enormous attention has been given to avoid and reduce the occurrence, it is essential to understand the common characteristics of those major accidents. One crucial characteristic of such accidents is that they always occur as an outcome of multiple failures in different safety barriers and their interrelation with unsafe acts by frontline operators. Major accidents were also found to be mostly caused by insufficient management quality and organizational as well as human factors (HF), since the changes that happened rapidly in the process industries in terms of new technology and high market competition have affected operators' work significantly. The more complex process installations, process control and safeguarding equipment are becoming, the bigger the risk of incorrect application can be and the more distant the operators will be from the real process. Meanwhile, in coping with the need to increase productivity and reduce costs, large turnover and reduction of staffs occurs while the work load is growing (Knegtering, et al., 2009).

HF has been given much less attention than it deserves in most companies' safety programs. Even if practitioners are gaining more awareness about the importance and benefits that can be achieved through the performance of HF analyses in their plants, there is a considerably great number that still view HF sceptically. An internal survey was conducted during this work within a well established company running in process industry in Germany. This survey has delivered findings[1] that HF is as a matter of fact

[1] no attempt is made for generalizing the condition

not an unfamiliar term for most of the managerial staffs, however, not many of them are aware of what HF really implies and is aimed at. The survey also presents the low level of acceptance to HF and its implementation in this company. This is an indication that there is still a lack of understanding about HF. Sceptics still see HF as ill-defined, difficult and expensive to apply (CCPS, 2007b). Such perceptions have convinced many people to wholly ignore or only partly include HF in their safety policy.

What they often fail to realize is that operators hold the key to reaching every goal the company is aiming at, and only if they were guaranteed safety and comfort during work, those goals can become achievable. Ignoring HF means ignoring their needs and requirements in order to successfully perform their work, which also means risking operational safety. HF will receive the attention it deserves if everyone was aware that the costs spent for implementing HF are barely comparable to the advantages it provides. The avoidance of fatalities, injuries, damage to the environment and the loss to capital are only some of the benefits of performing HF in a process plant. Increase in the operators' trusts in the company, in their working motivation, and the improvement in productivity and production efficiency are several others to mention.

In order to achieve these advantages, HF needs to be included in every stage of plant lifecycle, especially during the design of a process plant. Considering HF in early design phase can avoid the need of later changes during operation so that increase in efficiency and safety of operation will be achievable. Moreover, the incorporation of HF must be able to comprehensively take into account the diverse operator tasks and responsibilities during process operation. HF must cope with the requirements of a reliable information exchange between human operators and the distant processes they are supervising. The design of control system as a whole must therefore include consideration on how operator acts and responds to the provided information. Hence, an introduction of a reliable HF analysis technique that comprises works in field and in control rooms/centres, and is applicable for both plant design and operation is inevitably required.

1.2 Objectives

The lack of adequate systematic and well-structured means to incorporate HF in design and operation of chemical processes has been giving a big contribution to the slow penetration of HF in process industries. Hence, the objective of this work is aimed at the inclusion of HF in both plant design and operation, comprising the whole operators' activity and responsibility both during manual work and supervisory control.

As one of the most crucial aspects to maintain frontline operators' reliability, alarm management and the design of control system must incorporate HF and the consideration of operator actions especially in coping with abnormal situations. For this reason, a technique that provides the way to incorporate HF into alarm management is also developed in this work. The new technique will also enable an incorporation of HF into the design of control and alarm system, so that it understands operators' capabilities, requirements and limitations in performing supervisory control, particularly in dealing with process upsets.

The objective of the work is not to set new standards for the industry, but to encourage companies and individuals to apply the existing standards and operational guidelines in revealing the main HF issues and the most underlying problems in their facility by providing tools for a systematic HF analysis. Human error is not the cause of an accident, but the symptom of various underlying problems (Mackenzie, et al., 2009). Hence, in achieving the objective, this work developed methods that assist diverse users (HF analysts, engineers, plant managerial staffs or also operators) in finding the underlying problems in a system and to recognize necessary improvements so that operators' reliability and operation efficiency can be assured.

1.3 Scope of Work

The development of the HF method for plant design and the technique to incorporate HF into alarm management was based on the practical observation in several plants of Bayer CropScience AG, Germany. The case studies delivered in this work in order to better demonstrate the practical implementation of the developed methods are however hypothetical and simplified examples and do not represent any actual condition of the processes at that company.

The methods developed in this work are an enhancement of works conducted previously (Widiputri, 2007; Widiputri, et al., 2008). However, to enable an implementation in design phase and to provide an analysis of control room works, the previous works had been massively modified. New checklists, worksheets and questionnaires were developed corresponding to each of the new approaches. The development of the checklists and questionnaires was made based on the previous works and expert considerations related to this subject. Results provided by the methods should give direction to necessary recommendations provided by operational guidelines and standards.

The technique for HF analysis in control room developed in this work is aimed at providing a way to include HF into general alarm management. However, the technique only comprises a detail incorporation of operator actions in one particular stage of alarm management, which is the alarm prioritization. Prioritizing alarms is considered one of the most essential and effective ways to improve alarm system's performance.

CHAPTER 2

THEORETICAL BACKGROUND

2.1 Fundamentals of Human Error

Understanding human errors and their mechanisms has been a research focus in different areas for decades. Several views in defining what human error is and how it happens were offered by different perspectives. Rasmussen views human error and faults in performing a task as a phenomenon that cannot be defined objectively apart from the systemic context. A reference of what is intended and expected as an outcome of the task performance is required, to be able to judge whether the action taken was an erroneous one (Rasmussen, 1987). This opinion was also supported by Reason in his book saying that any attempt made to define human error or to classify types of errors must be made after a consideration of different intentional behaviour (Reason, 1990). Nevertheless, it is necessary to recall that having an intended action successfully done does not always mean that the action conducted was not erroneous. Human intention and the outcome of the action might be correct from one's perspective, which may vary from the intended and expected output of the function.

"There is no universally agreed classification of human error, nor is there in prospect". A taxonomy of errors is usually made for a specific purpose, and can consequently differ in a broad range depending on what the classification is based upon. Reason suggested one error classification based on the interaction between the basic error tendencies; which can include the ecological constraints, resource limitations, or various strategies; and the cognitive domains, which represent various stages or operation in human information processing (Reason, 1987). For this modelling, the mechanism of information processing in human mind is divided into three main stages: planning, storage and execution. Planning refers to the processes concerned with identifying goals and the means to achieve it, which will usually not immediately come to an execution, so that it is likely that a storage phase will intervene between those two stages. Errors that occur during all of the three stages can be classified into four main types of human failures: slips, lapses, mistakes and violations (Reason, 1990) as described in the following.

Slips are associated to failures in executing an action, even though the person has the correct intention. Due to different reasons, the action the person intended to perform is not conducted as planned. An example of slip is when an operator unintentionally enters a wrong set-point into a console by mistakenly typing the number 9 instead of 0, even though he knew exactly what the correct number was. Training will not prevent errors of this type, for even if everyone is well-trained and well-motivated, physically and mentally capable, they will still make occasional slips.

Lapses, similar to slips are failures conducted where the intention was correct. However, this kind of errors is associated with failures of memory, where actions are omitted or parts of the actions sequence are repeated. Lapses happen mostly during the performance of routine tasks in a familiar environment. The memory in this case is labelled as 'temporary' or 'volatile' memory that includes the short-term memory. Examples of this error type include forgetting list items, losing track of previous actions, misreading a display, or forgetting to press a switch.

Mistakes are the outcome of a failure in the plan to meet its objective. Errors of this type occur principally when someone lacks the idea of performing an action correctly. This can occur either because the plan or the intention was not suitable for the situation, or the situation was not foreseen so that no plan was available to face the situation. Mistakes can be further broken down into two types: the first one is failures of expertise, where plans are incorrectly and inappropriately conducted, and the second one is the lack of expertise. Misdiagnosing process parameters can be an example of this error type.

Violations happen when someone knows exactly what to do but decides not to do it. The intention of carrying out actions that might be contrary to organization rules and procedures is however not to cause harm or endanger the operation. Violations can happen while the operators are dealing with impracticable working procedures or out-of-date manuals. In the case where instructions are incorrect, violations can offer a prevention of an accident.

Another commonly used classification of error is the Generic Error-Modelling System (GEMS), which is based on the information processing mechanism proposed by a model from Rasmussen. This model differentiates human information processing into 3 levels, the skill-, rule-, and knowledge-based (SRK) tasks or behaviour. The lowest level of information processing is skill-based and includes mainly routine tasks where an automatic execution of actions is required. Skill-based behaviour relates to motor-skill in reacting to a current condition, without necessarily requiring conscious thinking. This behaviour is very commonly involved in industrial tasks, where in a familiar working environment, following a triggering event an operator knows spontaneously what the expected reaction is. The skill-based level is comparable with the 'execution' stage of human information processing.

Rule-based behaviour on the other hand requires a definition of the link between a condition and an action. An input sensed by one person will be interpreted into signs that characterise the condition in need of an action. The correct action will be defined by applying the rule: if <condition> then <action>. This level is comparable with the 'storage' stage in human information processing.

The highest level of information processing in SRK-based model is knowledge-based. To complete tasks of this category operators are required to consciously consider what action needs to be executed. It is very common that knowledge-based behaviour occurs in facing novel situations where no fixed rules are available. This level is comparable with the 'planning' stage of Reason's model, where an identification of the problem and assessment of the situation is required before able to decide the correct reaction.

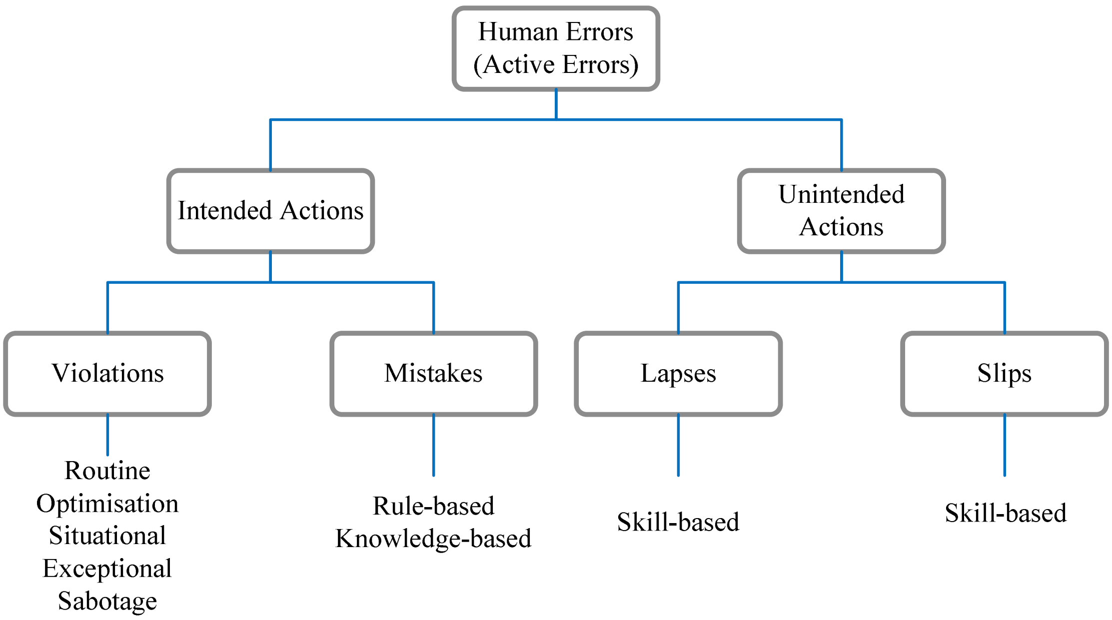

Figure 2. 1 Classification of human errors from the cognitive perspective (Reason, 1990)

SRK-based model differentiate errors based on the level of information processing where they are likely to occur. Skill-based errors are mainly described as unintended actions including slips and lapses. Mistakes on the other hand can be described as rule-based and knowledge-based errors, depending on whether they were caused through failures of expertise or by a lack of expertise itself. Figure 2. 1 demonstrates the error classification based on GEMS model, which summarizes the combination between Reason's classification and the SRK-based model from Rasmussen.

The error classification from the cognitive perspective has successfully described how different types of errors can occur in different levels in the human information processing system. The model however fails to define the underlying causations of these errors. The interrelation between human and the factors affecting their performance is not explained in this model and consequently, it strengthens the belief that human being with their limitations is the actual problem. Hence, the study about human error cannot end with the identification and classification of errors alone, but must proceed with the search for the causations. Only by understanding *why* people make errors, the occurrence can be prevented.

2.2 Human Factors (HF)

The term Human Factors (HF) corresponds to the interface between the scientific knowledge of human, facilities and procedural or managerial system, regarding all activities in different stages of a process, which can lead either to a better or poorer system efficiency, safety and reliability (CCPS, 2007b). This similar definition of HF was also suggested by the UK Health and Safety Executive (HSE) and the International Association of Oil and Gas Producers (OGP):

> „HF is the environmental, organizational and job factors, and human and individual characteristics which influence behavior at work in a way which can affect health and safety." (HSE, 1999)

> „HF is the interaction of individuals with each other, with facilities and equipment and with management systems." (OGP, 2005)

Figure 2. 2 shows the interaction of the 3 HF domains; facility/equipment, human/people and management system based on the OGP model. The domain

human/people represents the personal characteristics and behaviour, including factors related to fitness, skill, stress and fatigues. The facility/equipment domain includes considerations on physical characteristics of the workplace and design of equipment that the people need to work with. Meanwhile the management system domain can be considered as a framework under which operator works must take place. This domain includes working procedures, trainings and safety culture. The model shows an overlapping area between the 3 domains, which represents the focus of HF analysis in achieving a safe workplace. HF aims to fit the tasks and the environment to the person rather than forcing the people to adapt to those factors in a significant manner in order to successfully perform their work (CCPS, 2007b).

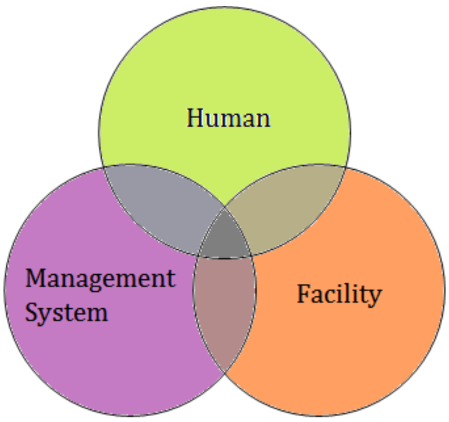

Figure 2. 2 HF domains based on the OGP model

Different from the cognitive perspective, HF views errors as a consequence rather than a cause of accidents. Although there are personal characteristics that are unchangeable, which influence the working performance of an operator in a significant manner, there are many more attributes that can be improved and adjusted to human's limitation in such a way that they reduce the likelihood of errors. Hence, HF always tends to search for the underlying causes of errors, which can be as simple as misplaced labels or a complex problem such as lack of trust to the company's safety policy.

2.3 Motivations to Consider HF in Process Safety

Human Factors (HF) as a study has its origin in the aviation industry, started with the consciousness that human plays a very big role in maintaining even the most sophisticated automatic system to operate expectedly. The irony of this fact is, apart from their ability to reliable information processing and decision making, human beings with so many weaknesses and limitations are left with such a huge responsibility. These weaknesses are often blamed to cause human errors that led to fatal accidents. With the expanding technology of aircraft and aviation industry, systems were becoming more complex and automation took over most of the responsibilities that previously were assigned to human. There is only one intention of performing this rapid shift in technology, which is to increase safety. Meanwhile, no matter to which degree the automation is increased, human being can never be eliminated from the system. The escalating system complexity leaves humans with even a bigger responsibility, and therefore a higher work load. Understanding this reality, many experts had dedicated their effort to comprehend how human beings interact with their surroundings and to eventually conclude that human errors are caused more by system inadequacies rather than their personal characteristics and limitations alone.

After gaining attention and responses in aviation industry, other industry branches such as medical, nuclear power plants and transportation realized the same problems in their fields. Improving the technology alone cannot further reduce the number of accidents occurring at their sites. The same issue was also acknowledged in process industry in early 1980s. Human factors deficiencies have been recognized to be the main cause of many major accidents in process industries. This has become a motivation to understand more about HF, regarding how to improve and optimize a working environment to best support and suit the operators' limitations so that they can deliver their maximal performance.

Figure 2. 3 demonstrates statistical data that address HF as a main cause of most undesired events in process industry. The figure illustrates results of a study conducted in petroleum refining industries to indentify the recurring human factors contributions to accidents. It is shown that 47% or around half of all the causes of incidents occurred in refining industries included elements of HF (Chadwell, et al., 1999). This result shows that seeking for technical flaws and people ineffective behaviour separately in analysing an accident is not adequate. It is crucial to also observe aspects behind the routine activities, for instance the organisational aspects, safety culture and training programs.

Understanding that many major accidents in process industries happened through inadequacies of various HF attributes helps people to realize that those accidents could have been avoided if the company had proactively incorporated considerations on HF throughout the plant lifecycle. Hence, avoidance of accidents becomes the main motivation to considering HF in process industry, which is in several regions already regulated and enforced by applied laws. However, one of the benefits of considering HF that people often disbelief is the increase in revenue since productivity and efficiency are improved, where at the same time, unplanned outages are reduced.

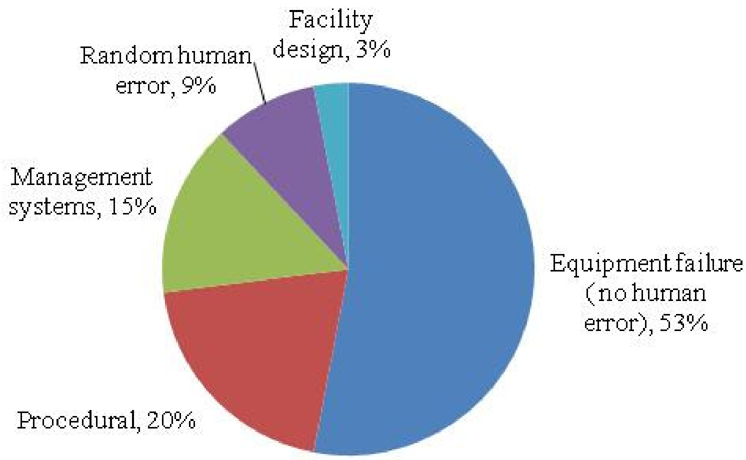

Figure 2. 3 Level 1 cause contribution factors of incidents in petroleum refining industries **(Chadwell, et al., 1999)**

In this chapter several accidents that attributed HF issues are discussed in brief and several others are tabulated in Table 2. 1. An explanation about regulations on HF in process industries and the business advantages offered by the implementation of HF is delivered subsequently.

2. 3. 1 Accidents that Address HF in Process Safety

Learning from accidents is the best way to avoid the same accidents from happening again. Understanding what had happened prior to the accident can help recognizing whether or not the similar deficiencies are found in other plants. During the last two decades, it has been acknowledged that the lack of awareness concerning HF and the insufficient design of HF aspects were the main cause of many major accidents in process industries. Several to mention are the Piper Alpha disaster, BP Texas City accident and the explosion of Texaco Refinery in Milford Haven, UK.

Piper Alpha

The Piper Alpha accident is one of the biggest events in process industry which has brought many insights about how important it is to incorporate the consideration of HF into safety concept. The disaster happened on an oil platform on July 6, 1988, where an explosion and resulting fire destroyed the whole platform and killed 165 people on board and 2 emergency response personnel, leaving only 59 survivors.

The Platform was first constructed in 1976 as an oil platform only, which was then extended to include gas production. In the first construction, four modules were located separately by using firewalls between each module. The safety concept had successfully brought the most dangerous sections distant from the personnel areas. The introduction of the new gas conversion part forced the utilization of the available spaces between the modules, which was previously intended as a safety barrier.

The disaster started with the burst of high pressure gas out of a condensate pump, which at the time was under maintenance. The pump was a backup pump, whose relieve valve (RV) was being overhauled on that day after one day extension, which still could not be completely finished until 6 pm. Permission to continue the service work on the next day was received and the tube where the RV should have been installed was sealed with a plate. Later long after shift change the primary condensate pump experienced a disturbance. A quick decision needed to be made, exactly when the shift leader found a permit to work (PTW) for the backup pump, without knowing that this PTW was prepared before the earlier shift realized that the overhaul could not be accomplished. No one present at that time realized the situation, that there was no RV installed at the backup pump and that this backup pump was still not ready for operation. The plate used to seal the pipe could not resist the high pressure and burst at once. The resulting amount of gas ignited instantly and caused an explosion. This initial explosion was the start of a huge fire and several other explosions, and within 22 minutes, the platform was totally destroyed.

Lessons learned

An investigation conducted by CCPS (CCPS, 2005) had delivered several key lessons that addressed complex HF issue, including:

1. Permit to work (PTW) system.
2. Communication problem during shift turnover.
3. Insufficient procedure to operate safety system, in this case the fire pump that had been switched to manual due to the presence of divers around the platform.
4. Insufficient design of the separating wall of the new module for gas processing, which was fireproof but not explosion proof.
5. Maintenance problems referring to corrosion.
6. Insufficient emergency response training for personnel, especially for the new platform.
7. Inadequate design of evacuation line and facility.

BP Texas City Refinery

The BP Texas incident marked the new millennium with one of the worst industrial disasters. The accident happened on March 23, 2005 at noon, after the lunch break. An investigation by U.S. Chemical Safety and Hazard Investigation Board (CSB) reported that the explosion and fires killed 15 people and injured 180 with total financial losses exceeding $1.5 billion.

The accident was initiated during the start-up of a raffinate splitter tower that was earlier under maintenance. The start-up took place in early morning where the tower was filled with a flammable liquid hydrocarbon up to a certain level, indicated by the control and instrumentation system. During start-up, the operator expected the level of the liquid in the tower to rise slightly over the desired level during operation, after years of experience. Therefore, alarm indicating that an inappropriate level of liquid has been reached was not an emergency alert for the operator during start-up. Unfortunately, the instrumentation did not provide the actual level of liquid in the tower to the operator, so that liquid that was flowing into the tower over three hours, which was actually contrary to the normal operating procedure, filled up the 57-m tower and overflowed the overhead pipe, down through a safety relief and at last reached the blowdown drum. The blowdown system was not properly redesigned for safety since it was an old unit built in the 1950s and had never been attached to a flare system. The overfilled blowdown drum released volatile liquid that evaporated right away into flammable vapour creating a huge vapour cloud surrounding the facility. Less than 10-m away from the blowdown drum it was found that at the exact time a pickup truck was parked with an engine still on, and was then believed as the source of ignition that backfired in an instance to the facility and caused a massive explosion (CSB, 2007).

Lessons learned

Findings of the investigation addressed that the BP Texas City Disaster was a result of both organizational and safety deficiencies at all levels in the corporation. BP was considered as not having the adequate method for analysing safety and had used wrong indicators to evaluate their safety performance. The misleading information had drifted them further away from preventing such a disastrous incident. Root causes of the disaster had been recognized as to involve following HF and organisational issues:

1. The absent of safety culture and major accident prevention programs
2. No inclusion of HF consideration in their training, staffing and work scheduling
3. No incorporation of good practice design in the operation of the unit

Texaco Refinery, Milford Haven

The series of events that led to the accident at the facility of Texaco Refinery started on a Sunday morning, 24 July 1994 following a severe weather condition. A lightning strike started a fire in the facility's crude distillation unit (CDU), which caused disturbances in several other units. The fire caused was however not the reason of the explosion that came several hours later at around midday. The explosion of the Texaco Refinery in Milford Haven was a result of a complex combination of deficiencies in management, control system and equipment, as to the investigation conducted by the U. K. Health and Safety Executive (HSE).

Prior to the explosion, flammable liquid hydrocarbon was continually pumped into a process vessel, whose valve at the outlet was closed due to a malfunction. The operators in the control room were not aware of the situation since the display showed that the valve was opened. The display did not provide overviews concerning process data such as mass and energy balance so that there was no way for the control room operators to have acknowledged what was going on with the operation. This event led to a series of other disturbances and released around 20 tonnes of a flammable mixture of fluid and vapour hydrocarbons. The vapour reached a source of ignition and exploded instantaneously afterwards (HSE, 1997).

Table 2. 1 Several Major Accidents that Addressed HF Issues **(CCPS, 2007b)**

Accident	***Human Consequences***	***Human Factors Issues***						
		Communications	**Training**	**Equipment**	**Maintenance**	**Decisions**	**Procedures**	**Human Machine Interface**
Flixborough, England, 1974: Cyclohexane release	28 fatalities 86 injured	Drawing of change done on shop room floor only.	The operators were not trained in hazard identification.		Not supervised by qualified engineer.	To bypass one reactor vessel with a temporary modification to allow the plant to continue to operate.	Poor management of change. No time limit set for the temporary change.	
Seveso, Italy, 1976: Dioxin release.	No fatalities directly attributed. Multiple illnesses.	Company did not communicate which chemicals had been released.		Bursting disc blew on a reactor vessel – set point too high. Reactor vessels inadequate.		Secondary receiver recommended by manufacturer to collect any vented material – not fitted.	Failure to follow operating procedures – Batch not finished and operation not shut down per normal shutdown procedures because of weekend holiday.	
Three Mile Island, Harrisburg, PA, 1979: Loss of control of nuclear reaction resulting in destruction of reactor core.	None	A near miss at another unit was not communicated to this unit.	Training for operators not adequate – no feedback to students.	Turbine trip. Subsequently, pilot-operated relief valve (PORV) sticks open.	Two block valves left in closed position after maintenance 2 days before.	Operators reduced coolant water flow into reactor attempting to prevent flooding – caused meltdown.		Operators misled by control panel – poor design. Over 100 alarms – not prioritized. Warning light showing valves closed obscured by maintenance tag.
Bhopal , India, 1984: Release of Methyl Isocyamat (MIC)	Est. 8,000 fatalities 300,000 injured	No alarm ever properly sounded to warn of gas cloud. Failure to provide MIC treatment information.	Half to two-thirds of skilled engineers had left prior to the accident.	Insufficient scrubber capacity. Flare tower disconnected. Vent gas scrubber in inactive mode. No gas masks available.	Pressure and temperature sensors did not work – pressure gauge under reading by 30psig. Refrigeration plant shut down to save costs. No regular cleaning of pipes and valves.	To store 10 times more MIC than required on site.	Poor evacuation measures. No temporary management of change.	No online monitor for MIC tasks. No automatic sensors to warn of temperature increase.

Lessons learned

The investigation by HSE provided some key lessons from the occurrence of the explosion at Texaco Refinery in Milford Haven. In the following several lessons learned from the accident are crystallized addressing the contribution of both technical measures and HF as the causes:

1. Inadequate emergency response procedure that failed to overcome with process upsets
2. Inadequate control and instrumentation system
3. Insufficient display configuration and operator interface
4. The absent of good management of change (MoC) and overall maintenance
5. Inadequate hazard analysis and assessment

2. 3. 2 Regulation and Legal Requirements

The integration of consideration about human operators in process industry has been addressed in many regulations in different parts of the world. Some of the regulations and standards have explicitly put the requirements to incorporate HF into plant lifecycle, whereas some others impose the assurance of occupational health and safety in order to reduce the number of people killed, injured, or made ill by work. In this section several regulation requirements in different regions are described.

HF Regulations in the European Union (EU)

Within the European Union (EU) the control of major accident hazards is regulated under the *Council directive 96/82/EC* issued in 1996, also often referred to as the Seveso II Directive. The directive is aimed at the prevention of hazards involving dangerous substances and at the limitation of the consequences of such accidents for man and the environment. The latest amendment to the SEVESO II Directive was issued on 16 December 2003 (*Directive 2003/105/EC*). SEVESO II was the first regulation to introduce checks on human role in the chemical process safety. The directive acknowledged the significance of interaction between humans and the system on the overall process safety (European Union, 1996; Kariuki, 2007).

In Germany, SEVESO II Directive is implemented through the *"12. Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes-12. BImSchV"* of 26 April 2000. The act put explicit requirements to take the necessary safety-relevant precautions to avoid false operation, to provide suitable operating and safety applications, as well as to conduct adequate trainings of the personnel in preventing major accidents (Bundesministerium der Justiz, 2010). Meanwhile, in the United Kingdom SEVESO was transposed into COMAH (Control of Major Accident Hazards) regulations, which ensure that businesses "take all necessary measures to prevent major accidents involving dangerous substances and limit the consequences to people and the environment of any major accidents which do occur". Three organizations are responsible for the enforcement of COMAH, which are the Health and Safety Executive – HSE, the Environment Agency – EA (for England and Wales) and the Scottish Environmental Protection Agency – SEPA (HSE, 2010).

HF Regulations in the United States of America (USA) and North America

The Occupational Safety and Health Administration of the US government in their capacity as the regulator require the inclusion of HF as one of the 12 core elements in process safety management (PSM) system. In OSHA's standard *29-CFR-1910.119* inclusion of HF into the Process Hazard Analysis (PHA), design of procedures, and training programs is emphasized (Bridges, et al., 2010). The guidelines to compliance of these standards are provided by the *Directive CPL-02-02-045* issued and revised by OSHA in 1994 (OSHA, 2000). The inclusion of HF in PHAs is also required by regulations for risk management programs, *40 CFR 68.24* of the US Environmental Protection Agency (EPA) (Bridges, 1994).

In Canada, the consideration of HF and ergonomics is regulated under the *Canada Labour Code Part II, the R.S., 1985, c. L-2* with the purpose to prevent work-related accidents and diseases in companies and organizations (Department of Justice Canada, 2010b). The codes are the formal written enactment of the Canada Occupational Health and Safety regulations – *SOR 86-304* (Department of Justice Canada, 2010a).

HF Regulations in Asia

The Korean Occupational Safety and Health (KOSHA) enacted the Industrial Safety and Health Act (ISH Act) in 1981 with the purpose to prevent injuries and disease and to maintain worker's health. ISH Act then served as the groundwork for the full implementation of industrial accident prevention policy (Kang, et al., 2004). In 1990

KOSHA issued the *Presidential Decree No. 13053*, latest amendment in 2010 that regulates the enforcement of the occupational safety and health act. In South Korea the specific term of HF is commonly known as human factors engineering (HFE), and has been taken into account as one of the important issues for safety improvement. The implementation is however still relatively limited and comprises mostly the nuclear industry. Generally, HF analysis is performed by means of HRA (Human Reliability Analysis), which is a quantitative technique to predict the likelihood of human error.

Similarly in Indonesia, HF has not been massively adopted into safety promotion programs. Acts related to occupational health and safety have been however enacted since the 1970s, one of the initial ones is the *Indonesian Act No.1/1970* about occupational safety at work. The practical implementation of this act is generally based on different international standards, such as the ILO Code of Practise, the ISO and OSHA standards. In the past decade there has been a significant move in interest for incorporating HF in design and operation of process plants, which is however mostly captured in the gas and petroleum industries.

All of the enforced regulations and the related compliance directives emphasize companies to identify potential human errors and to reduce the frequency and consequences of such errors as part of an overall process safety management (PSM) program. Nevertheless, many practitioners claim that there are momentarily too many regulations without any reference how to practically implement HF consideration during plant design, operation, maintenance and construction. Several guidelines, such as the OECD Guiding Principles for Chemical Accidents Prevention, Preparedness and Response and different CCPS guidelines provide the golden rules in achieving a safer workplace and avoiding accidents. However, not all recommendations suggested by the available guidelines are suitable for every situation, and therefore, a careful consideration in selecting the most appropriate ones is necessary. Moreover, many of the regulations and directive address HF only in term of how to design a safer working environment and do not focus on the search for error causations and the underlying problems.

2. 3. 3 Business Value

The performance of HF in a plant or a facility will deliver many benefits in addition to the improvement of process safety. The impacts of better safety quality will result in not only the reduction in near-misses and human errors potential, but also in an increase in working performance, which will improve productivity and production efficiencies. Ultimately, a reduction in lifetime costs associated with maintaining and re-engineering the facility and equipment will be achievable (CCPS, 2007b). The cost need to be expended in performing HF is considerably insignificant if compared to the significant performance improvement and to the fact that fatalities are potentially avoided.

Some useful proofs of how HF can substantially bring benefits to business values are provided by several case histories. BP Grangemouth took actions to improve the quality of human factors at their site after recognizing numerous incidents attributable to human errors. After a 3-years period a 10% improvement in plant reliability and a 25% reduction in costs were achieved. A human factors improvement conducted in the Air Products and Chemical, Inc. within 2 years-period has resulted in a 60% reduction in the number of controllable outages. ExxonMobil, Inc. as another example has also successfully reduced their outages by 80% within 5 years after the implementation of human factors improvement had been initiated. These success stories should motivate the implementation of HF properly and proactively throughout plant lifecycle as a cost effective way to improve process safety (CCPS, 2007b).

2.4 Work of Operators in Complex Systems

The definition of system complexity described in this work is based on the level of responsibility and mental workload that one operator holds during operation. How to judge the degree of both attributes is very questionable and includes subjective opinions from people that might claim to know the system at its best. However, a complex system has become a frequently used expression to describe a system where a large number of components are involved; whose changes in status and parameter might occur frequently, and to certain extent could happen unpredictably and very rapidly (Cochran, 1997).

The technology modernisation in process industry has resulted in computerization and automation of process functions. The need to computerize and automate appeared as markets are being enhanced, productivity must be increased and processes have to be therefore extended. From the awareness that human operators have their limitations in supervising and monitoring systems, that can each consist of several complex processes, automation has become an absolute requirement. The aim of automation is basically to eliminate work of operators at points where operator's interference is not feasible for any reason. Automation aims therefore at the assurance of process and personnel safety, as well as production efficiency and product quality.

However, the introduction of computerization and automation had brought other, much bigger issues for process safety. In this chapter, some most common problems with automation are discussed after the description of operator's role and responsibility in complex systems.

2. 4. 1 Role of Operators in Complex Systems

Operators, no matter what their limitations are, can never be eliminated from a system and indeed, still hold the most important role among all elements in the system. A minimum number of personnel is required in maintaining the operation to run. An increasing degree of automation can only reduce the number of operators down to a certain point, where no further reduction will be possible. In fact, if the degree of automation is heightened even further, it would be possible that the required number of operator will increase again due to i.e. maintenance activities, as shown in Figure 2. 4 (Ivergard, et al., 2009).

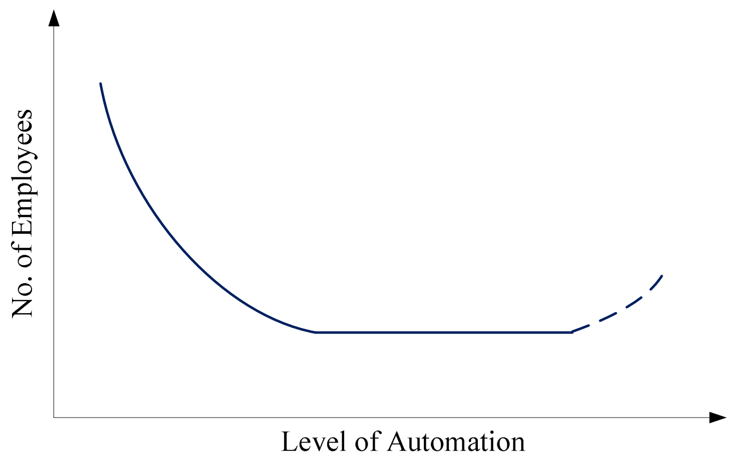

Figure 2. 4 Number of personnel with the increasing degree of automation

Operators working in a complex system must stay and work as a team. The system is too large and too complicated for one single person to comprehend and handle. In their relationship with the system, human operators have the role to manage the operation to run smoothly, at the desired condition and status. The activities are nowadays facilitated by distributed control systems (DCS) that provide the operators with information from every measuring point all over the process on a single visual display unit (VDU). All parts of the process are brought together and control is possible to be conducted from one centralized control room. DCS appeared in place of conventional control system while VDUs replaced the old control panels. The changes imply directly to operator load, since they influence the information exchange between operators and the process.

Traditionally, operators in operating and controlling a process have a direct contact to other system elements such as the machineries. The procedure is quite simple; the operators give input to control equipment like valves, wheels or levers, usually decentralized and spread all over the plant, which will directly affect the process. Process will deliver a feed-back to an analogue instrument in form of panel mounted displays, either decentralized or brought together in a control room (remote operation). With the introduction of computerisation and automation, there was a shift in this relationship between operator and the process. Nowadays, operators do not always have a direct contact with the process, since control is basically automated. Whenever intervention is necessary, operators have the possibility to interfere through computers, based on the information provided by displays. Operator's responsibility becomes one of checking standards and monitoring the automatically controlled process, rather than to conduct manual tasks outside the control room (Ivergard, et al., 2009).

Nevertheless, there are only a few numbers of processes that completely assign its control functions to computer. In many processes, a direct intervention of operators to the system is still required, if not in routine operation (for non-automated functions), then during process upsets and maintenance. Figure 2. 5 demonstrates such a process, where process intervention through analogue control systems is still required. The dashed line shown in the figure represents the operator's authority in some cases, to intervene with the automated functions through computers. Even if most of the functions in one process are fully automated, operator involvement can never be completely eliminated.

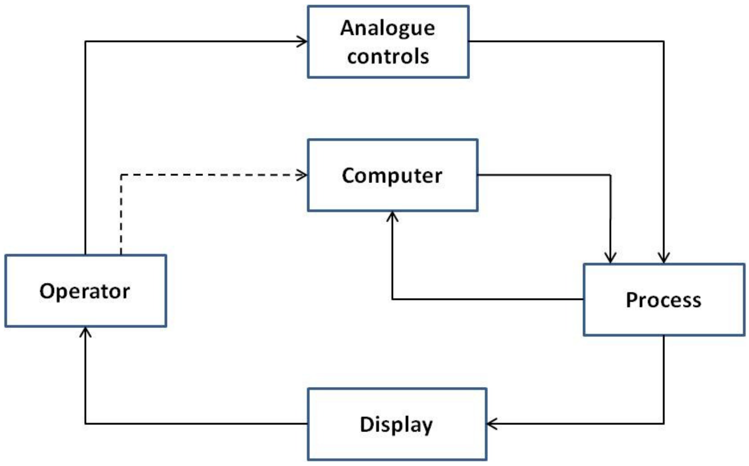

Figure 2. 5 Model of human operator's role in semi-automated complex system, adapted from **(Ivergard, et al., 2009)**

Process automation can only be increased to a certain degree, without entirely removing human beings from the operation. A discussion about the degree of automation is delivered later in this chapter. In process industries, processes that run semi-automatically still outnumber the full-automated ones. In semi-automated complex systems, operators must conduct on-site work in addition to the monitoring tasks they ought to complete in control rooms. A brief description of operator responsibilities during on-site work and work in control room is delivered in the followings:

Work in field (manual/on-site work). Operator responsibilities that can be classified into field work or manual/on-site work are for example:

1. Process start-up/shut-down
2. Sampling and sample proofing
3. Level checking
4. Acknowledging process state at analogue devices in field
5. Manual feeding/charging
6. Cleaning work
7. Loading/unloading
8. Inspection and maintenance

Work in control room (supervisory task) requires operators to conduct several typical tasks, which include the followings (Stubler, et al., 1996):

1. Process monitoring or supervisory control
2. Fault detection
3. Fault diagnosis and cause identification

4. Decision-making to select desired response
5. Execution of the accurate corrective actions

Work of operators both in field and in control room is aimed to maintain the operation to run its normal state, and to overcome with upsets or abnormal situations whenever disturbances occur. The sequence of operators' responsibilities during both process conditions is illustrated in Figure 2. 6. The x-axis of the diagram describes the time sequence, irrelevant to the real duration of each action, whereas the y-axis shows the different process status, from normal to abnormal condition.

During a normal operation, process monitoring is the main task to be performed both in field and in control room. Due to one or another disturbance, the operation can move away from its normal state, approaching abnormal condition. The system needs a certain time to be able to detect that a deviation is occurring, before alarm will be activated. Alarms following a process deviation will notify the operators of the abnormal situation, which will require certain corrective action to be performed. It is crucial for the operators to understand the cause of alarm activation, in order to select and decide the most proper solutions. Following the implementation of a corrective action, the system will require some time to react, before moving back approaching the normal operation line.

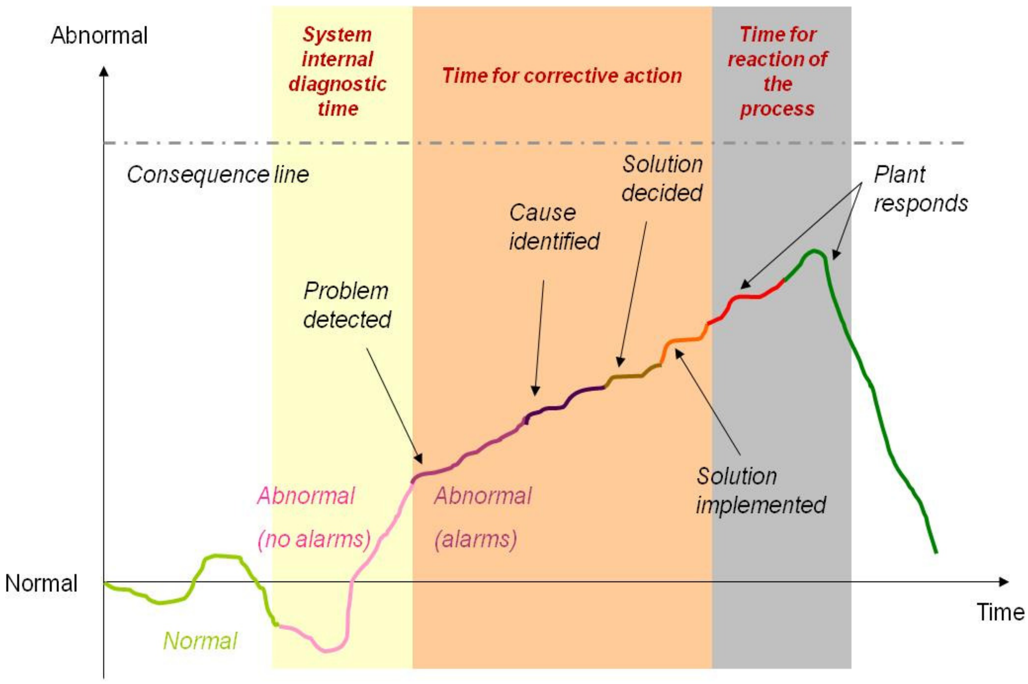

Figure 2. 6 Flow of an operation and operator responsibilities **(Rothenberg, 2009)**

Even though operator tasks during a normal operating state are not trouble free, it is very obvious that in abnormal situation/upsets operator load will be heightened. Unfortunately, during this stressful phase operators are required to give their best performance, since their decision and how they implement the solution holds the key for the avoidance of undesired events from happening. Any mistaken action taken during this phase can result to an unwanted consequence that can trigger a disaster. This is the reason why in various discussions about work in control rooms, experts tend to stress on the importance of managing abnormal situations. In order to understand human information processing during abnormal operation, a model was developed by Cochran as illustrated in Figure 2. 7.

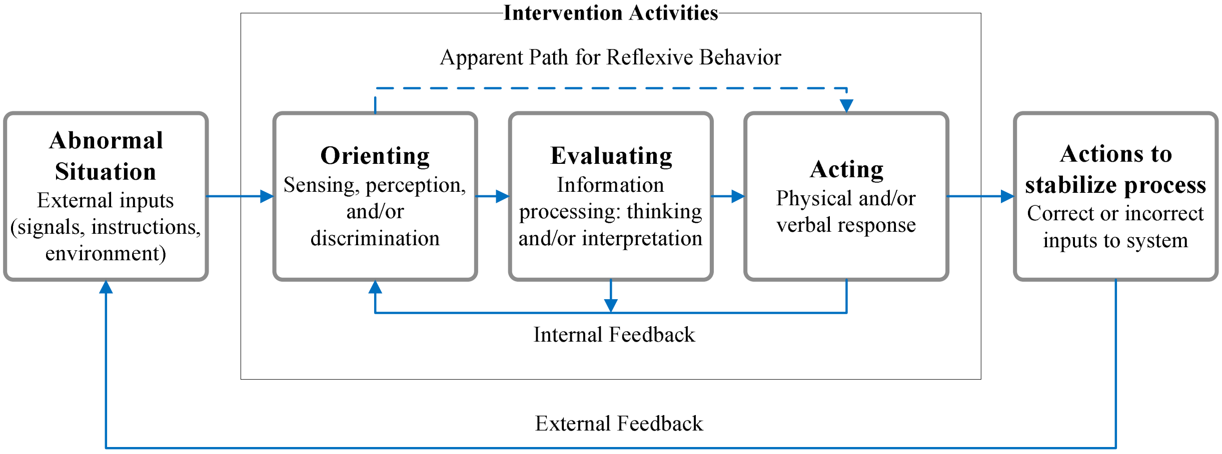

Figure 2. 7 Model of operators' information processing in abnormal situation **(Cochran, 1997)**

2. 4. 2 Problems with Computerisation and Automation

As mentioned previously, the introduction of computerisation in process industry has led to the implementation of distributed control systems (DCS). Computerisation was a solution to many industrial problems, starting with economic profitability, improvement of both process and personnel safety, and to the fulfilment of community requirements to conserve nature. As a result of computerisation, automation becomes an inevitable way in achieving these goals. Nevertheless, computerisation and automation has brought many cons apart from the pros it offers.

Table 2. 2 lists some benefits and problems caused by the shift from conventional control system to remote operations due to the introduction of computerisation in process industries (HSE, 2002).

Table 2. 2 Issues arising through the change to remote operation,
adapted from **(HSE, 2002)**

Change	*Potential Benefits*	*Potential Problems*
Reduced manning levels	Cost reduction	Increase in work load, stress, difficulty in covering for absence
Digital control systems	Cheaper maintenance, reliability increase	Technical problems, e.g. during power failure
Computer interface to control system	Early detection of problems through reliable readily available data	Information overload for operator, additional skill required, reduction of awareness of the real process status
Higher degree of automation	Consistency improvement, workload reduction	Over-reliance to the system, vigilance reduction, boredom
Distant control room from plant	Increase in personnel safety	Problem in communication, reduction in term of know-how concerning the process physically
Use of communication devices, e.g. radios	Communication improvement	Technical problems, e.g. during power failure

Since it has become very clear that computerisation and automation can contribute in causing extra load to the operators, deciding what to automate and to what degree the operation needs to be automated cannot be done without a thorough consideration. In the next section, allocation of functions between human operator and machines is discussed closer, as well as the influence of the degree of automation on operator's work load.

2. 4. 3 Allocation of Functions and Levels of Automation

Automating functions that are dangerous for people or are impossible for human operators to complete is most of the time unavoidable. However, due to many problems that might arise as a consequence of system changes, a threshold must be met. In order to maintain the complexity of the system at a certain tolerable and acceptable degree, it is sometimes desirable to keep several functions conducted manually. Therefore, functions have to be carefully analysed and closely observed, in assuring the correct and most proper allocation between human operators and machines.

One of the oldest techniques for the allocation of functions in the history of ergonomics and HF study is the so-called MABA-MABA ("men are better at, machines are better at"), which was later changed into HABA-MABA, with "human" replacing "men" for ethical reason. This technique utilizes comparative lists between human abilities or limitations and those of machines, which were referred to as Fitts Lists (Fitts, 1951; Hancock, et al., 1998). Basically, there are several general considerations in allocating functions to human or machines; these are summarized after (Woodson, 1992) and some of which are discussed in the following:

1. **Environmental Constraints.** Several constraints that are not supported by human physiology are for instance extreme atmospheric pressure, temperature, noise, vibration, radiation and risks arising from explosion, fires or chemical contamination.
2. **Speed and accuracy.** Human response cannot compete with the capacity of a machine in terms of speed and accuracy. Thus allocation to human must be made based on their capacity.
3. **Overload.** Humans tend to accumulate load either physiologically or psychologically. Under stress and pressure, effectiveness and accuracy after a long period of work can become very uncertain.
4. **Physical strength and fatigue.** Humans are extremely limited compared with machines in terms of how much force they can apply, and for how long.
5. **Storage capacity.** Even though human has a great capability to store large amount of information for a relative long period, their ability to retrieve this information is somewhat limited. Machines capability in storing or retrieving information may not always be better than human, since is wholly subject to its design.
6. **Interpretation of and response to unexpected events.** While machines can completely quit in facing unexpected events, especially ones they were not designed to cope with, human have the unique capability to re-evaluate every situation. They may come to a less-than-perfect solution, but can result in the rescue of the operation.
7. **Learning.** Learning new things require certain period of time for human operators, while machines operate right away after being programmed and operated.
8. **Cost.** As long as humans are used properly, they often are the least expensive component of a system.

Allocating functions between human and machine based only on the differences between their capabilities and limitations is nowadays not considered as adequate anymore. Since human and machine need to work together in a good synchronization, it is crucial to emphasize the interaction and co-operation between the two (Noyes, et al., 2001). There is a gray area that must not be forgotten between manual and automated system, the semi-automated one, which is the most common type of chemical industry these days. In such system, human and automation must support each other to give their best performance. In Figure 2. 8 different levels of possible combination between the proportion of human responsibility to machines are listed (Sheridan, 1987).

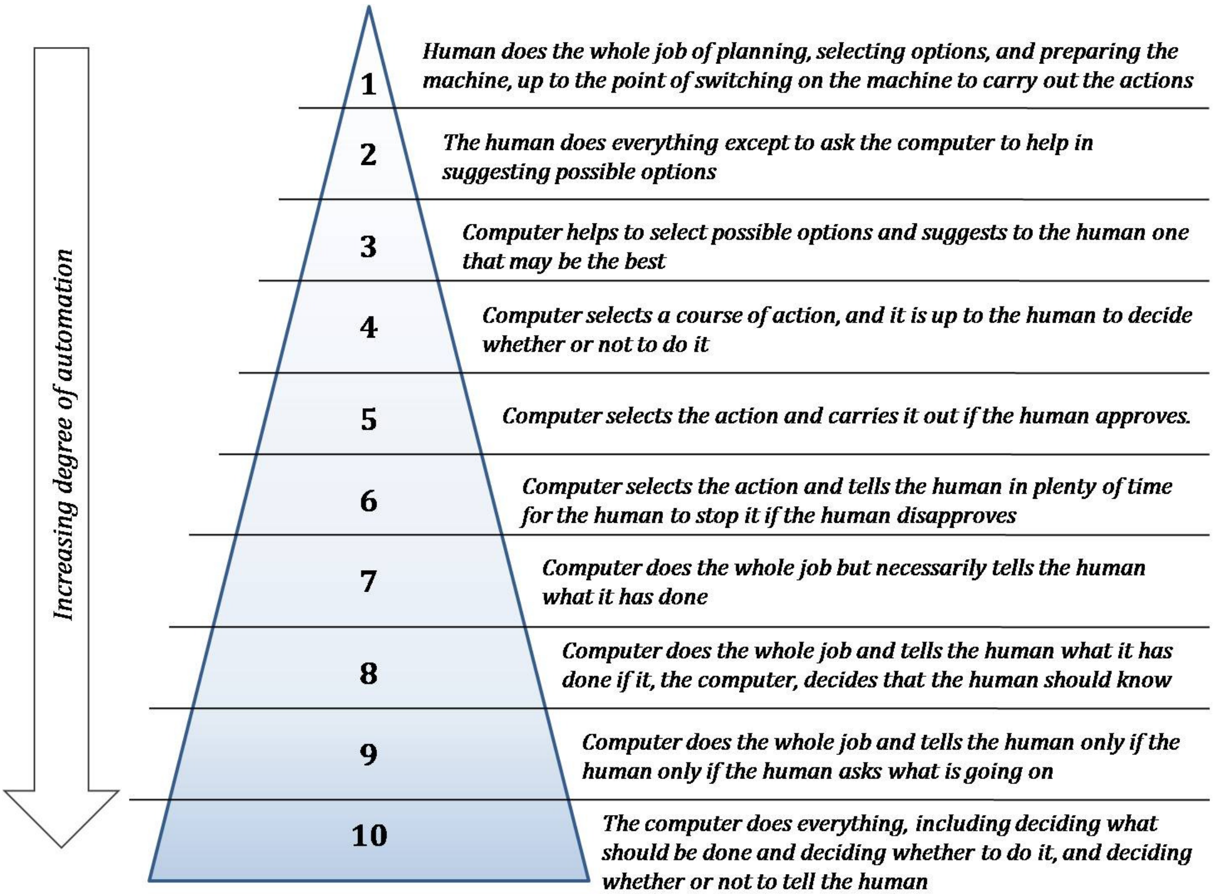

Figure 2. 8 Sheridan's scale of human-machine functions in complex systems

2.5 Performance Influencing Factors (PIFs)

In performing their work human operators can never stay in isolation; there is always an environment where an interrelation between them, the machines or equipment they work with, and the workplace characteristics occurs. The situation has been very clearly described in the previous section about work of operators in a complex system. One important point to be noted is that regardless of their capabilities, human beings can be very easily influenced by their surroundings. Hence, understanding the underlying cause of any incorrect action possibly performed by human operators requires an analysis of the total man-machine systems, in order to identify factors that affect operator's performance during work (Widiputri, 2007).

Factors, which in combination with basic error tendencies can enhance or degrade human performance, are referred to as the performance influencing factors (PIFs) or in most human reliability analyses (HRA) are often labelled as performance shaping factors (PSF). These factors are however not automatically associated with human error. They will vary continuously from the most influencing to the most irrelevant ones. There are factors which are generic and will influence performance in most industries, but the most are more likely to be important only in specific industries. For that reason, it is difficult to produce a list of PIFs that could be used as an audit in any given situation (Embrey, 2000).

PIFs can generally be divided into two areas, the external and internal PIFs. The external factors are basically those, which influence the human from its surrounding. This consists of especially technical equipment design and managerial conditions such as working procedures and instructions. The internal factors on the opposite are the factors that represent the personal characteristics of the individual, including their mental capabilities, motivations and skills. Table 2. 3 shows an example of PIFs grouping (Dalijono, et al., 2006).

Table 2. 3 Performance Influencing Factors (PIFs)

<table>
<tr><th colspan="3">Performance Influencing Factors (PIFs)</th></tr>
<tr><td colspan="2">External PIFs</td><td>Internal PIFs</td></tr>
<tr><td>Technical Condition</td><td>Managerial Condition</td><td rowspan="2">e.g.:
• Skills
• Communication
• Stress Level
• Motivation</td></tr>
<tr><td>e.g.:
• Time span to complete the task
• Temperature
• Vibration
• Noise</td><td>e.g.:
• Frequency of task
• Instructions (form, procedure)</td></tr>
</table>

In addition to these main groups, Swain and Guttmann added another group of PIFs that represent the condition resulted from system's non-conformance to human operator capabilities and limitations. The latest factors are grouped into stressors PIFs, which include psychological and physiological stressors. Some examples of psychological stressors are high and jeopardizing risk and work that is monotonous or meaningless. Physiological stressors on the other hand relate with fatigue and the feel of hunger or thirst (Swain, et al., 1983).

Regardless of the grouping into internal, external or stressor factors, PIFs can differ broadly depending on the kind of activities performed by the operators, e.g. in nuclear, aerospace and chemical industries. Therefore, in analysing a man-machine system all PIFs relevant to the work must be identified and defined at the first place. Based on previous works, the PIFs classification used in this work had been identified for typical operator tasks in process industries, mainly in less-automated plants where a considerable amount of manual and field work still exists besides the works conducted in control room. These PIFs are described later in Chapter 5.

2.6 Distributed Control System (DCS) and Alarm Systems

Distributed control systems (DCSs) were introduced in process industry around more than 3 decades ago, replacing the centralized one. DCS normally utilizes VDU-based consoles in place of panel mounted consoles. This shift in technology has brought a direct impact on control room instrumentation, and therefore influenced also operators' responsibility and workload. That the rapid introduction of DCS in process industries has resulted in not only many positive system improvements but also in many additional safety problems, was not instantly recognized by system designers. After many years of practical experiences, it became evident that designing DCS requires more than just technical knowledge concerning the process and control system.

The design of DCS includes many aspects that directly and/or indirectly affect operator performance. These can include the system architecture, selection and design of hardware and software, security design, process input/output design, communication facilities, as well as operator and engineering interfaces (Lukas, 1986). Since the dominant issue in designing process control is to minimize the potential of human error both during normal operation and upsets, an understanding about the way operators perform their tasks and how they interact with the DCS is very crucial to have (Zwaga, et al., 1994). Hence, designing DCS must include HF considerations to help operators avoiding upsets, diagnosing and ultimately responding to those upsets that do occur (CCPS, 2007b).

As one of the main key aspects of DCS-design that have the responsibility to maintain a reliable information exchange between the operators and the process, design of alarm systems becomes an essential issue in assuring that the process runs within the safe operation zone. Further discussion concerning alarms and alarm system is delivered in the following section.

2. 6. 1 Alarm, Alarm System and Alarm Management

Alarm may be a familiar word to people working in process industries, especially those in charge in operating process control. However, in the application, there is often a misdefinition between alarms and warnings or other annunciations/signals. Due to this issue, alarms, which are supposed to provide assistance for operators in maintaining the operation flow, often become the source of load and troubles in gaining situational awareness. Several basic definitions of alarms are summarized from several sources should help in defining an alarm:

> "Alarms are signals which are annunciated to the operator typically by an audible sound, some form of visual indication, usually flashing, and by the presentation of a message or some other identifier. An alarm will indicate a problem requiring operator attention, and is generally initiated by a process measurement passing a defined alarm setting as it approaches an undesirable or potentially unsafe value", (EEMUA, 1999).

> "It is generally considered that the role of alarm is to give warning of impending danger, albeit in varying degrees of severity. An alarm can be an unexpected change in system state, a means of signalling state changes, a means of attracting attention, a means to arousing someone, or a change in the operator's mental state", (Stanton, 1994).

From the above definitions, the first rule in designing alarms can be extracted as; alarms must indicate that the system is facing a problem or an undesired change of process status, which requires operator's attention to quickly respond to it. Consequently, other annunciation such as warnings, information about parameter changes in a tolerable range, or reminder to maintenance cannot necessarily be defined as alarms and must be treated separately.

There is a recommendation of several characteristics that a good alarm and alarm system must meet according to (EEMUA, 1999). A good alarm must be:

a) relevant: not spurious or of low operational value;
b) unique: not duplication of another alarm;
c) timely: not long before any response is needed or too late to do anything;
d) prioritised: indicating the importance that the operator deals with the problem;
e) understandable: having a message which is clear and easy to understand;
f) diagnostic: identifying the problem that has occurred;
g) advisory: indicative of the action to be taken; and
h) focusing: drawing attention to the most important issues.
If each alarm is designed to meet these desired characteristics, then a good alarm system will be achievable.

An alarm system as a broader term than alarm is defined in ISA-SP 18 as the collection of hardware and software that states an alarm, transmits the message to be displayed to the operator, records the message, and generates alarm metric reports, which must also be capable of filtering plant status information to be presented to operators. Sometimes it is desirable to discard some information rather than to present everything and overload the operators with information (Bransby, et al., 1998). A good alarm system must successfully provide helps to the operators to:

1. maintain the plant within a safe operating envelope. A good alarm system helps the operator to correct potentially dangerous situation before the ESD (Emergency Shutdown Systems) is forced to intervene,
2. recognise and act to avoid hazardous situations,
3. identify deviations that could lead to financial loss, e.g. off-specification,
4. better understand complex process conditions. Alarms should be an important diagnostic tool that provides assistance for operators during an upset.

Alarm management on the other hand includes the processes and practices for determining, documenting, designing, monitoring, and maintaining alarm messages from process automation and safety systems. It is in essence the design and implementation process for the entire redesign (rationalization) of alarm systems. The implementation and role of this process is demonstrated in a life-cycle model illustrated in Figure 2. 9 (Dunn, et al., 2005).

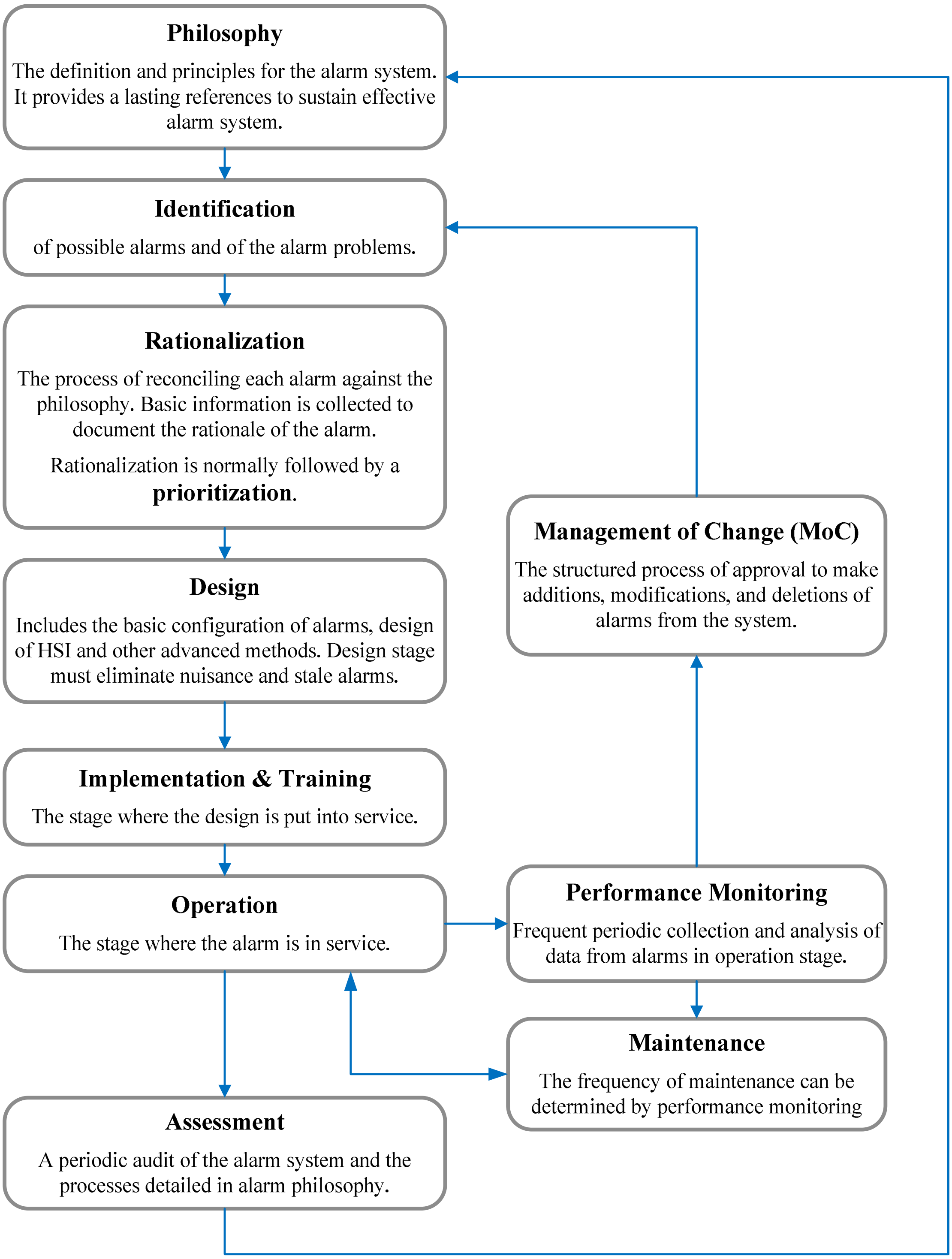

Figure 2. 9 Alarm management lifecycle **(Dunn, et al., 2005)**

Many guidelines, although none of which is up to the date this work was written is standardized nor regulated, have been regionally developed and are available to help the design and management of alarm systems in diverse industrial branches. These guidelines are de facto the industrial best-practises, which are obtainable in (EEMUA, 1999; HSE, 2002; NAMUR, 2003; Dunn, et al., 2005).

2. 6. 2 Most Common Alarm Problems

The installation of an alarm system has a significant contribution in adding problems to the operators, if not performed properly. This sub-chapter will list the mostly recognized problems with alarm systems experienced in process industries. The numbering in the list does not show the relative significance of each problem.

1. **Over-alarming or alarm flood.** Alarm flood can be considered as the most complex problem. Due to over-alarming, during upset conditions operators are very likely to receive too many signals from the alarm systems in too short time frame (Koene, 2000). This can lead to overloading operators' capacity in processing the incoming information that it will be extremely difficult for them to understand the real status of the process.
2. **Lack of clarity of real alarm.** The lack of clarity of real alarms is also caused due to over-alarming. Being too cautious of every parameter change during operation often leads system designers and engineers to install alarms into the system more than necessary. This is sometime resulted from safety analyses such as HAZOPs (Hazard and Operability study). A lot of the introduced alarms are basically not an alarm, since they only inform operators about tolerable changes.
3. **Stale or standing alarm.** Stale or standing alarms are those that remain activated for extended time period, since they require no clear respond from operators and keep standing even after an action has been taken (Dunn, et al., 2005). The term standing alarms is used for shorter term activation whereas stale refers to alarms that remain active almost all the time.
4. **Chattering alarms.** Chattering alarms are those alarms that are activated and cleared again and again in a very short time frame. This kind of alarms is symptom of improperly designed alarm systems, or parts of the process whose parameters vary extremely (Rothenberg, 2009).
5. **Nuisance and perpetual alarm.** These alarms are caused by mainly poor chosen set points, poor maintenance of the equipment or when the alarm logic does not show the status of the equipment for instance alarms that are still active on idle equipments (Atwood, et al., 2007). Moreover, if such alarms went off, no exact response needs to be conducted instantly. These types of alarms distract operators from the real alarms and train them to intentionally ignore incoming alarms.

6. **Hidden alarms** are actually a consequence of the implementation of DCSs, since displays only provide a small window for operators to monitor the change of process status. Sometimes the system successfully alerts the operators of an active alarm, however for inexperienced operators it could be a problem to locate where the exact problem is (Shaw, 1993).

2. 6. 3 Improving Alarm Performance through Prioritization

Even though improving alarm performance requires more than subtraction alone, reducing the number of configured alarms or removing unnecessary alarms can attend to a significant increase in efficiency. This will address to solving two major alarm problems; flooding and nuisance alarms. However, removing alarms from the system requires a systematic assessment of the current system performance. Such systematic is known as alarm rationalization, which includes which points to alarm, determining point of activations and other alarm response information such as potential causes, appropriate operator responses as well as the consequences of error, which is normally followed by the setting of priority (Rothenberg, 2009).

Another suggested means to improve alarm system performance is the alarm prioritization. With a proper priorities distribution, operators are acknowledged with the actual most critical situation during an information flood. This way, operators can filter the information they are receiving, thus can build a better situational awareness. Alarm prioritization should also be linked with an operator response procedure to assist the selection of necessary response, especially to alarms with high priority. Several common techniques to prioritize alarms are discussed below, followed by a brief discussion about some extension of those techniques.

I. Alarm prioritization matrix

The EEMUA publication no. 191 suggests a prioritization of alarms according to two attributes; the severity of consequences and the available time to respond to alarms. Priorities are defined in 3 levels, high, medium and low priorities, which are to be differentiated from emergency alarms leading to automatic emergency shutdown. An example of alarm matrix to assist the analysis is recommended by NAMUR NA – 102 (Figure 2. 10).

Priority

Response time	Severity of consequences		
	Shutdown	Off-spec	Production delay
< 5 min	High	Medium	Low
5 - 20 min	Medium	Low	Low
> 20 min	Low	Low	Low

Priority

Figure 2. 10 Example of a prioritization matrix **(NAMUR, 2003)**

The matrix shows the relation between the seriousness of the consequences caused if operators ignore or omit an alarm and the approximate available time to respond to the corresponding alarm. The consequence can be classified into three levels of severity, for instance process shutdown, product off specification and a production delay with decreasing severity respectively. The alarm priority reduces as the consequence severity decreases and as more time is available for operator to conduct corrective actions.

II. Alarm prioritization using scoring table and urgency values

Based on the classic technique to prioritize alarms as discussed above, many experts attempted to put more logic and systematic behind the relationship between consequence severity and available time to respond. An extension of this technique is described by Rothenberg in his book which recommends the use of a scoring table and urgency mapping in assessing priorities. The technique adds additional subjective numerical weight on the severity of each consequence and elicits the urgency values from the available time. Priorities of alarms can then be calculated by multiplying the consequence-severity values and the multipliers obtained from the urgency values. Following is a short example to describe how this technique works (Rothenberg, 2009).

Let an alarm given a priority based on the consequences related to 3 attributes; safety, environmental damage and financial loss. The severity of these consequences is levelled into low, medium and high, complementary a 'none' to describe no possibility of a certain consequence to happen can as well be applied. Weight will then be subjectively added to each severity for every consequence. As example in the above table (Table 2. 4), a high severity of safety impact is weighted with '150' (the weight is arbitrary and can be set in any ranges). Afterwards, relative to the first settled weight, weights are to be added for other severity levels (low and medium) for the same attribute 'safety impact'. Finished with one attribute, the weighting continues with the next one. For this purpose, the first attribute that was completely assigned with subjective weights is taken as a baseline for the next weighting process. In this example, the baseline would be safety impact. By taking 'high' safety impact as a comparison, 'high' environmental damage will be next evaluated. Supposedly, the company sees that environmental damage in the same severity level with safety will cause bigger impact, than the weight for high severity environmental damage must be assigned with a bigger number, i.e. 200. Afterwards, the same procedure is applied until all attributes and their associated severity levels are weighted. An alarm will be evaluated by selecting the scores (severity number) from the table that best represent how the alarm might impact all 3 attributes.

Table 2. 4 Example of alarm priority scoring table **(Rothenberg, 2009)**

	Consequence severity			
Consequence	None	Low	Medium	High
Safety	0	50	100	150
Environmental	0	75	125	200
Financial	0	50	75	100

As some alarms are to be attended more quickly than other, or in other words, have bigger urgency than others, the severity values obtained in Table 2. 4 must be adjusted to reflect the urgency of an alarm in avoiding a particular incident. For this purpose, multipliers are determined to represent the urgency level. These multipliers will adjust the severity number, which will later be mapped to a priority table to assign a proper priority. Table 2.5 and Table 2.6 show an example of multipliers table and table of alarm priority break points respectively.

Table 2. 5 Example of urgency values and the corresponding multipliers

Time available	*Multiplier*
≤ 3 min	1.5
> 3 but ≤ 10 min	1.2
> 10 but ≤ 20 min	1.0
> 20 min	0.8

Table 2. 6 Example of alarm priority mapping table

Priority	*Breakpoint value*
High	From 350 and above
Medium	From 250 to 349
Low	From 100 to 249

III. Function-based alarm prioritization

Alarm prioritization can also be done by prioritizing functions identified in the process. The function-based alarm prioritization approach (Basso, et al., 1998) suggests a prioritization based on 3 steps:

Step 1. Identification and organization of plant functions, specifically those functions involved with annunciation,

Step 2. Prioritization of plant functions, by operational importance, for each plant operational issues, and

Step 3. Assignment of individual alarm priorities based on their association with a specific plant function.

The implementation of the approach aims to reduce the inconsistency in assigning the prioritization to each single alarm, since this activity can be very labour-intensive and prone to human error. From the functional perspective, prioritization of alarms should be done not only for normal operation state, but especially should focus to abnormal states of the process. Since in abnormal situation, maintaining the awareness of relative importance between incoming alarms is the most difficult thing to achieve. Thus, a priority should be assigned to all alarms relevant to one process function. Following are the major considerations of using this approach:

1. Consistency in alarm grouping and prioritization. Alarms will be prioritized based on the common importance with a single set of priority assignments applicable to the group.
2. Alarm grouping will be done through an operationally relevant way, since staffs are to monitor and observe the system from a functional perspective, relevant to plant operating goals and states.

3. An organization of plant functions by importance, with respect to each operating state, would provide a basis for grouping alarms for prioritization purposes. Priorities for individual alarms would be assigned with respect to the base function priority.
4. The approach provides way to compare priority among alarms and function groups to reveal inconsistencies.
5. Compatible to be converted into widely implemented computer operating systems such as Microsoft and Oracle environments.

Although most industrial plants use three levels of prioritization for their alarms, there are also several plants that implement four levels prioritization; critical, high, medium and low priority. However, there is a danger in using too many priorities since a clear distinction between each priority can be missing. The use of the fourth priority can be on the other hand very useful if implemented consistently for very few situations only, such as cases where life, serious plant damage or major financial and environmental impacts are jeopardized (Rothenberg, 2009).

Table 2. 7 Recommended alarm priority distribution

Priority level	*Distribution*
High	5%
Medium	15%
Low	80%

Moreover, an effective priority distribution of alarms is very crucial to help the operators during upsets. Since a large number of alarms can be active during this abnormal situation, there should be only a relative small and manageable portion which accounts to high priority alarms that will direct operators to acknowledge the most significant disturbances (NPD, 2001). The distribution of priorities recommended by EEMUA is as shown in Table 2. 7 above (EEMUA, 1999).

2.7 Safety Analysis Methods

Safety analysis holds a critical role in the development of complex process plants, which can generally involve two main activities; hazard identification and risk analysis. The first activity aims at the recognition of possible hazards with significant consequences such as loss of life or serious damage to facilities and the surrounding environment, as well as the possible causes of such hazards. Identifying possible occurrences of critical hazards will provide assistance in avoiding them from happening, and hence to prevent their undesirable consequences. In safety analysis, hazard identification is often followed by a risk analysis, where a quantification of potential risk associated with each identified hazard takes place. Risk assessment will deliver consideration in judging the tolerability of potential risks in the facility.

In order to perform a safety analysis, both qualitative and quantitative methods are available, which enable the performance of both hazard identification and risk assessment. The most common and widely-used methods for safety analysis in the process industry are discussed in brief in the following (CCPS, 2000; Crowl, et al., 2001).

2.7.1 Qualitative Safety Analysis

Several qualitative safety analysis methods that are commonly implemented during development of process plants are the *Preliminary Hazard Analysis (PHA), the Hazard and Operability (HAZOP) study, the Failure Modes and Effects Analysis (FMEA), What-if Analysis and Checklists*. Among these methods, HAZOP and FMEA provide an adequate systematic structure for the identification and analysis of potential hazards, as well as the causes thereof. Hence, more detailed explanation concerning both methods will be delivered here.

2.7.1.1 The Hazard and Operability (HAZOP) Study

The Hazard and Operability (HAZOP) study is a qualitative means in identifying possible hazards and problems during operation in a process plant (NSW Government, 2008; Crowl, et al., 2001), which was first developed by ICI in the 1960s and started to be widely implemented in chemical process industries after the Flixborough disaster. The examination is carried out by applying guidewords on each process parameter to discover how deviations from design intent can occur, and whether those deviations can cause hazards. The guidewords provide a way to brainstorm every possible cause of an incident, yet some of the causes may be very unlikely and can be disregarded form the analysis. For every recognized hazard, necessary safeguards or modifications on existing safeguards will be proposed. The typical practical implementation of HAZOP can be seen in Figure 2. 11 whereas the basic guidewords used for the analysis are tabulated in Table 2. 8 (Rausand, et al., 2004).

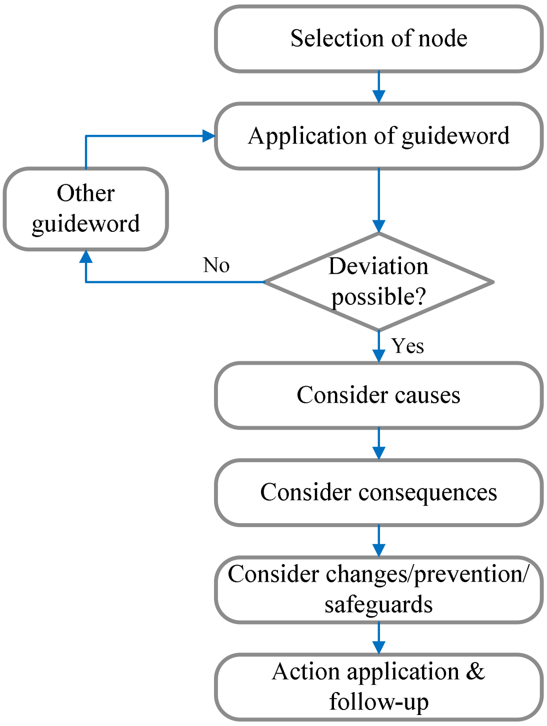

Figure 2. 11 HAZOP procedure illustration, adapted from **(NSW Government, 2008)**

Table 2. 8 The standard HAZOP guidewords **(Rausand, et al., 2004)**

Guideword	***Meaning***	***Example***
No	None of the design intent is achieved	No flow when production is expected
More	Quantitative increase in a parameter	Higher temperature than intended
Less	Quantitative decrease in a parameter	Lower pressure than normal
As well as	An additional activity occurs	Different valves close at the same time
Part of	Only some of the design intention are achieved	Only part of the system is shut down
Reverse	Logical opposite of design intention occurs	Flowing in opposite direction
Other than	Completely substitution	Liquid in the gas piping

The performance of HAZOP studies in the process industries requires a contribution of experts from different backgrounds to assure its comprehensiveness. The team for such analysis must be at the least consisted of:

a. Project engineer
b. Commissioning manager
c. Operation manager

d. Instrument/electrical engineer
e. Safety engineer

and depending on the necessity can be enhanced to also include the operator team leader, maintenance engineer, supplier representative as other appropriate specialists (Rausand, et al., 2004).

The results delivered by a HAZOP analysis are summarized in a report, and can be utilized to improve the system configuration and operation. An advantage of HAZOP in addition to its systematic examination is the multidisciplinary study required during its performance. This enables the inclusion of operational experiences of different parties involved in the team that can address among others the lessons learnt from past incidents.

To overcome with various needs in discovering hazard potentials, HAZOP has been modified or adapted into several other analyses techniques, also referred to as the non-traditional HAZOPs. Some examples are the *Control/Computer HAZOP – CHAZOP* (Kletz, et al., 1995), the *Safety Culture HAZOP – SCHAZOP* (Kennedy, et al., 1996) and *Human (Error) HAZOP* (Stanton, et al., 2005). The basic difference during the implementation of these non-traditional HAZOPs lies on the selected guidewords used for the identification of possible deviations.

2.7.1.2 The Failure Mode and Effects Analysis (FMEA)

The FMEA was one of the first systematic techniques for failure analysis and is widely used in the initial stages of system development. The performance of FMEA has the purpose to assure that all potential failure modes and their effects have been considered and the proper condition to prevent those failures has been made available. Nowadays, FMEA is also known as FMECA with an additional "C" that expresses the "criticality" of various failure effects. The distinction between the two terms is no longer obvious, since consideration on criticality has become a common part of an FMEA and is always included in such an analysis (Rausand, et al., 2004).

The performance of FMEA/FMECA basically follows the 4 main steps: system structure analysis, failure analysis, risk ranking and team review, and the identification of corrective actions. System structure analysis will break down the system into manageable units, typically functional elements, depending on the scope of the analysis. Corresponding to the identified hierarchy of the system, a worksheet will then be prepared to assist the analysis of potential failures in each function. An example of an FMEA worksheet covering the most relevant columns is provided in Figure 2. 12.

System: Performed by:

Ref. drawing no.: Date: Page: of

Description of unit			Description of failure			Effect of failure		Failure rate	Severity ranking	Risk reducing measures	Comments
Ref. no	Function	Opera-tional mode	Failure mode	Failure cause or mechanism	Detection of failure	On the subsystem	On the system function				
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)

Figure 2. 12 Example of FMEA worksheet (Rausand & HØyland, 2004)

In the first 3 columns of the worksheet, a description of the unit is listed, including the definition of functions and the various operational modes for each element (e.g., idle, standby, running). In the next 3 columns (columns 4, 5, and 6) potential failures are listed, together with their causes and the possibilities for detection of those failures. In columns 7 and 8 both the local and global effects of identified potential failures are listed. The failure rates are listed in column 9, representing how likely a failure would occur. In the next column of the worksheet (column 10) the severity of the failure effects is ranked and listed. Afterwards, necessary risk reducing measures need to be identified and listed as well in the worksheet.

In the third step of FMEA/FMECA performance, which is the risk ranking and team review, a calculation of the so-called *Risk Priority Number (RPN)* is normally carried out. For this calculation, several variables that were analysed in the previous stage (during failures analysis) need to be classified and expressed in ranks to enable a simple quantification of the risk. These variables are the possiblility for failure detection (*D*) listed in column 6 in the worksheet, the likelihood of failure occurence or failure rate (*P*) listed in column 9, and the severity of failure effects (S) listed in column 10 in the worksheet. For the calculation in this analysis, these variables are classified and assigned with different ranks. An example of the classifications of variables D, S and P is provided in Table 2. 9 (Pillay, et al., 2003).

Table 2. 9 Example of the ranking of variables in FMEA

Rank	*Detection (D)*	*Failure Probability (P)*	*Effect Severity (S)*
1	Failure would almost certainly be detected	Very unlikely	No noticeable effect
2 – 3	Failure remains undetected until the next inspection	Remote	Failure that causes low level of annoyance to the operator but does not result in system deterioration
4 – 6	Failure remains undetected until system performance is affected	Occasional	Failure that causes high level of annoyance to personnel or results in noticeable but slight deterioration of the system
7 – 8	Failure remains undetected until system performance is severely reduced	Probable	Failure results in significant degradation of system performance or minor injuries to personnel
9 – 10	Failure remains undetected until system performance degrades to an extent that function fails	Frequent	Failure results in serious damage to the facility or causes major injuries to personnel or fatality

The RPN is accordingly defined as

$$\boldsymbol{RPN = D \times P \times S} \qquad \textbf{Equation 1}$$

Corresponding to the values of each rank defined in Table 2. 9 above, a greater value of RPN will express a more severe condition and hence a bigger risk potential. Correspondingly, the design team or the engineers will be provided with the insights concerning the most critical process elements in the whole system and can accordingly conduct effort to preventing the undesirable failure effects.

2.7.2 Quantitative Safety Analysis

Besides the qualitative performance of a safety analysis, quantification is in many cases required for the risk assessment. A quantitative analysis needs therefore to be carried out after an analysis of system structure and plant condition, in order to enable an analysis concerning the probability and frequency of possible hazards, and also the risk level. For this purpose, several quantitative safety analysis methods were developed, and some of the most well-known and commonly implemented ones are the *Fault Tree*

Analysis (FTA) and the *Event Tree Analysis (ETA).* A detailed description of both methods is delivered in (CCPS, 2000).

2.8 Mathematical Algorithms

In analysing different criteria in order to make decisions subjected to various HF problems, working with numerical values is sensed to be a more comfortable and convenient way. Even during an analysis that takes place qualitatively, the interpretation of human logical thinking in linguistic language into numerical values can provide a more comprehensible description concerning HF issues in the plant and to correspondingly settle the most proper solutions to the identified problems. Several common calculation techniques can be applied to support the decision-making process in problems associated with multiple attributes (goals/criteria) and the classification of those problems in finding the most suitable solutions. In this section, a brief description about techniques for multi-criteria decision making (MCDM) and classification techniques is delivered.

2.8.1 Techniques for Multi-Criteria Decision Making (MCDM)

Many decisions that people need to make in the real life involve multiple objectives, either it is a decision in private life for example in choosing a holiday destination, or in professional life such as strategic decision making in a company. Due to the limitation of capacity, human mind cannot always cope with complex calculations, so that in dealing with complex decision analysis people tend to use approximate methods, as often referred to as 'rules-of-thumb' or also 'heuristics' (Goodwin, et al., 2003). These heuristics can lead to quick decisions and are often well adapted to particular situations.

However, if the information to be handled simultaneously becomes too large and too complex, heuristics cannot lead to an optimal decision. In dealing with complex problems, decision makers need to consider and explore trade-offs between multiple attributes, so that quick decisions are not suitable anymore. In coping with problems associated with multiple objectives, techniques for decision analysis are available, which are classified under the multi-criteria decision making (MCDM) techniques. The main idea of such techniques is to break the complex problem down into smaller parts, so that the decision maker can acquire better understanding of the problem. MCDM techniques are widely diverse; each has its own characteristics. There are many ways to further classify MCDM techniques, for example based on the type of data available for the analysis process. An example of taxonomy of MCDM techniques is provided in (Triantaphyllou, 2000).

The Analytical Hierarchy Process

One of the most widely applied MCDM techniques is the analytical hierarchy process (AHP) proposed by Saaty in 1980 (Saaty, 1980). The basic idea of the method is to translate the subjective assessment of relative importance to a set of overall scores or weights (Fülöp, 2005). AHP is applied for making judgments about the priorities between alternatives of solutions, if examined with respect to different decision criteria in achieving the main goal. Figure 2. 13 below demonstrates how a problem is set into a decision hierarchy for decision analysis purposes using AHP.

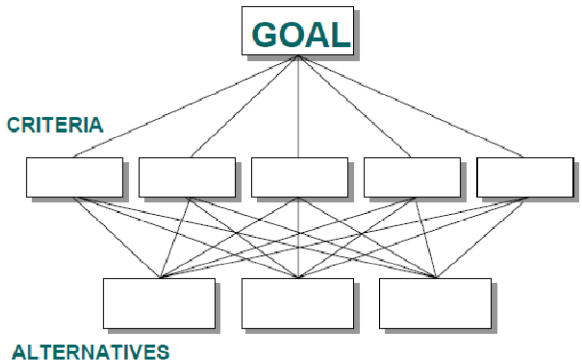

Figure 2. 13 A typical decision hierarchy for decision analysis with AHP

The methodology of AHP is based on pair-wise comparisons between decision criteria C_j (j = 1,..., n) in terms of their relative importance if compared one with another. For the relative comparison purpose, Saaty suggested a nine-point scale expressing the preference intensity for one criterion against another (Table 2. 10). The pair-wise comparison can be arranged in an n x n reciprocal matrix C. By using the eigenvector of this comparison matrix C the weights of each criterion can be elicited. Let w_j denote the weights of all n criteria where $\sum_{j=1}^{n} w_j = 1$.

Table 2. 10 Fundamental scores for importance comparison **(Saaty, 2008)**

Intensity of importance	***Definition***	***Explanation***
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favour one activity over another
5	Strong importance	Experience and judgement strongly favour one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals of the above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A logical assumption

Similar to the elicitation of weights for the criteria, AHP uses pair-wise comparisons to determine the relative performance of the alternatives subjective to each decision criterion. Let A_i (i = 1, ..., m) describes m types of possible alternatives. The scores in the nine-point scale will be once again used to express the relative importance of the performance of one alternative in comparison with another relating to each criterion C_j. The relative performance value of alternative A_i when it is considered in terms of criterion C_j is denoted with a_{ij} and the sum $\sum_{i=1}^{m} a_{ij}$ is as well equal to 1. In taking the final decision, the judgement of which alternative is taken as the best solution to the problem (in the maximation case) will follow the relationship below:

$$\boldsymbol{A_{Best}} = \mathbf{max}_{\boldsymbol{i}} \sum_{\boldsymbol{j=1}}^{\boldsymbol{n}} \boldsymbol{a_{ij} w_j} \quad \text{for } i = 1, 2, ..., m \qquad \textbf{Equation 2}$$

Since people's feeling and preferences remain inconsistent, and since this inconsistency increases with the increase of the size of the pair-wise matrix, a method to check the consistency of the judgement has to be done before accepting the calculation results. Saaty suggested a way to check the consistency by calculating the Consistency Ratio (*CR*), which is the ratio of the Consistency Index (*CI*) to Random Consistency Index (*RI*).

$$CR = \frac{CI}{RI} \qquad \textbf{Equation 3}$$

To obtain *CR, CI* is calculated from the comparison matrix following:

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \qquad \textbf{Equation 4}$$

where λ_{max} denotes the biggest eigenvalue of the pair-wise comparison matrix and *n* is the number of elements to be compared.

The Random Consistency Index (*RI*) was obtained from large number simulation runs, using a sample size of 500 to 1000, and is dependent on the order of the matrix. These values are tabulated in Figure 2. 14 above. The matrix is considered to be consistent and acceptable when the value of its *CR* is lower or equal to 0.1 ($CR \leq 0.1$). If the value of *CR* exceeds 0.1, a revision should be carried out to the pair-wise judgement.

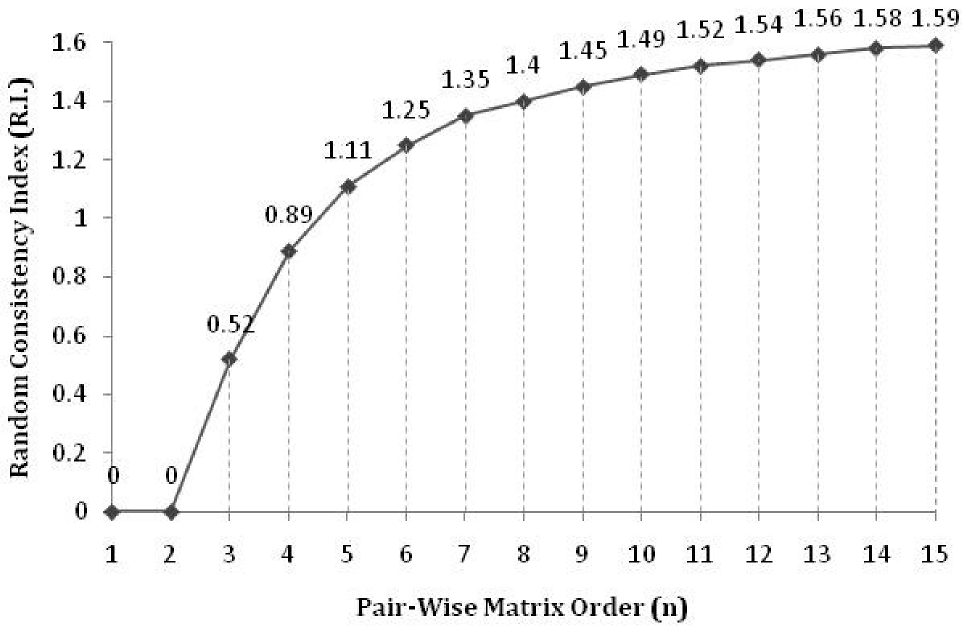

Figure 2. 14 Random consistency index (*RI*) (Saaty, 2008)

2.8.2 Classification Methods

In the decision making process, it is sometimes very necessary to classify problems in order to have a better focus in searching for the most proper solutions. From experiences, a relation between a problem and the possible solutions to it can become a common know-how in a particular field. This relationship can be interpreted as a data set that classifies common problems and pairs them with the most typical solutions.

Hence, by classifying one problem into a certain class or type, solutions to the problem can be searched within a narrower area. In this section, one of the simplest and most widely used algorithms applicable for classification purposes is delivered briefly.

The *k-Nearest-Neighbor (kNN)* Algorithm

The idea of *k-Nearest-Neighbor (kNN)* was first introduced by Cover and Hart in 1967 (Song, et al., 2007; Cover, et al., 1967). *kNN* is one example of many instance-based learning methods, which assumes that instances can be represented as points in a Euclidean space. The basic principle of *kNN* is the classification of a query instance q, by comparing it to a stored database of training examples (Mitchell, 1997). Every time a new query instance encounters and needs to be classified, its relationship with the previously stored data or training examples is examined in order to set target value for this new query instance. Instances in this matter are assumed to be consisted of several attributes a_r so that for a particular instance x, the attributes can be expressed as

$$\langle a_1(x), a_2(x), \ldots, a_n(x) \rangle$$

where $a_r(x)$ denotes the value of the r^{th} attribute of instance x. If instance x_i is assumed to be the training examples stored in the database, then the distance to be examined between a query instance x_q and x_i is defined to be $d(x_i, x_q)$ where

$$\boldsymbol{d(x_i, x_q) \equiv \sqrt{\sum_{r=1}^{n} \left(a_r(x_i) - a_r(x_q) \right)^2}} \qquad \textbf{Equation 5}$$

Each training example is assigned with a certain target value so that the database stores the examples of the form $\langle x, f(x) \rangle$, and the value of $f(x_q)$ returned by the algorithm as an estimation of the target value for the query x_q is simply the most common value of f among a number of training examples (the amount is expressed with k) nearest to the query x_q. k for this purpose can be arbitrarily determined, depends on the requisites and problem definitions.

As an example, in Figure 2. 15 a set of training examples is plotted on a two-dimensional space, where the target functions are valued as positive and negative and represented with "+" and "-" respectively on the diagram. A query point is shown as the blue point labelled with q. It is now desired to examine the distance between q and the training examples within the dataset, in order to classify q to either positive or negative class. In this example k is determined as 5, so that $f(q)$ is defined by the most common f value of the nearest 5 training examples to the query point q. From this example it can be noted that the 5-Nearest-Neighbor classifies q as negative, since 4 among the five nearest neighbouring points are assigned with “-“.

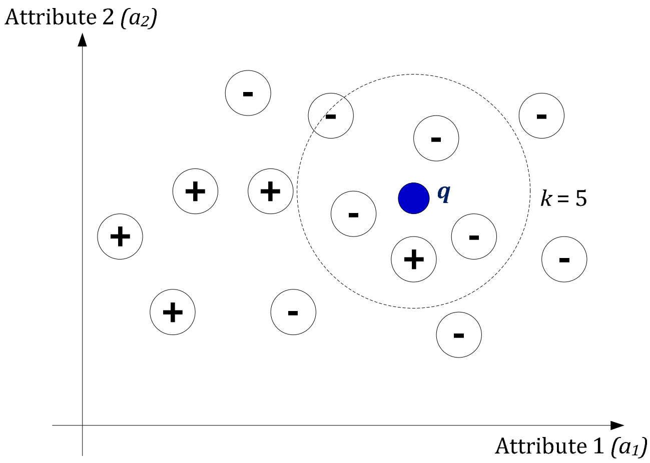

Figure 2. 15 Example for a classification with *k-Nearest Neighbor (kNN)*

The *kNN* algorithm is one of the most widely-used approaches for classification and has been enhanced to comply with more complex problems and to improve its robustness and reliability. Several variants of this approach are available for example by weighting the k neighbours according to their distance to the query point or by weighting the significance or relevance of the attributes of each instance, which are taken into account in the classification process. This way, instances will be examined relevant to the most contributing attributes.

CHAPTER 3

RECENT DEVELOPMENTS IN HF STUDIES

With the escalating awareness that as a crucial element of a system, human operators deserve the opportunity to be given an adequate working condition and safety assurance, techniques to analyse HF in process industry have become a very essential need. Approaches, both qualitative and quantitative, have been developed over time with the aim to find the way to providing the operators with better working environment. In this chapter, several techniques to incorporate HF consideration are described, and a discussion about the advantages and disadvantages will be pointed out subsequently.

3. 1 Methods for HF analysis

Methods for HF analysis in process industries are aiming to the recognition of possible errors by human operators during the performance of their work. Recognizing and understanding human limitations and the underlying problems that can force humans to conduct errors is considered to be the key in avoiding them from happening. Unfortunately, revealing these problems is not as trivial as it seems. A systematic way is necessary to adequately analyse the interaction between operators and their working environment. In the following sub-chapters, several common techniques to analyse HF are briefly discussed, beginning with the most commonly implemented HF method, the Task Analysis.

A. Task Analysis

Task analysis is the fundamental approach to identify and analyse every operator task. To initiate the analysis, preliminary plant investigations and observations must be performed, and technical information (P&IDs, flow-charts), operating manuals, documents of the local conditions (plant lay-out, map of location) and personnel information (training, personnel qualification) should be at assistance. There are a variety of different techniques in performing task analysis, several to mention are the well-known hierarchical task analysis (HTA), the operator action event tree (OAET) or the cognitive based ones such as the critical action and decision evaluation techniques (CADET) and the influence modelling and assessment systems (IMAS).

Despite the advantages that each technique may offer, there are essential disadvantages of those techniques in general that must be underlined. Varying between those well-known techniques, the disadvantages may include one or more of the following aspects (CCPS, 1994):

- Some are not focusing on the observable aspects of operator behaviour
- Some provide no analysis on the mental process underlying operator behaviour
- Some provide no description of temporal characteristics of the tasks, e.g. during abnormal condition
- Some provide no description of interaction between operators and control system
- Some are not emphasizing on the required communication among team members
- Some provide no classification of tasks into different categories
- Some provide no qualitative description of the technical system being operated

Although task analysis aims at the prediction and prevention of possible errors, this method is to be differentiated from the so-called human error analysis. TA is the fundamental technique, whereas human error analysis (HEA) is a domain where TA can be implemented.

B. Techniques for Operators Actions Analysis

Several techniques that investigate and observe operator actions during plant operation were developed to prevail over a deficiency of TA or HEA, which is the absent of the search for the causes of human errors. By understanding what people must do during performance of their work, the causes why errors are executed can be recognized. Examples of such methods are; Identification in the P&I-Diagram, Disturbance Compensation Graph and the Bar-Graph Method (Dalijono, et al., 2004)

The above mentioned methods are not widely-recognized and commonly implemented for several drawbacks that must be emphasized, such as; they do not provide information about the distance between different equipment to be operated simultaneously, some of the methods do not give prediction of consequences of an error and they do not investigate operator actions during both normal and abnormal conditions concurrently. The points which are not delivered by those existing methods are the most essential information in understanding why operators conduct incorrect actions, especially during abnormal situation. This called for a development of a new method for analysing operator actions in process industry (Dalijono, et al., 2005).

3. 2 Human Reliability Analyses (HRA)

The basic incorporation of consideration on human error is brought into safety analyses through the derivation of numerical human error probabilities for a use in fault trees. Nevertheless, experts have believed that the quantification is often misplaced and will lead to a totally incorrect analysis result. Thus, there have been numerous attempts to optimize human reliability analysis (HRA) from time to time, by taking more qualitative parts of such analyses into account. Practitioners emphasize the importance of this qualitative insight to understand comprehensively how errors could occur and how to avoid them (CCPS, 1994). One of the well-known HRA methods is the *Technique for Human Error Rate Prediction (THERP).*

The performance of THERP is basically identical to the event tree in the chemical process quantitative risk analysis (CPQRA). The basic step is the identification of elementary tasks; followed by a definition of an error occurrence scenario structured top down to the bottom level, whose human error probability (HEP) is contained in the THERP-Handbook. Lastly, a total quantification of the error probability can be calculated, which will then be applicable for a use in fault tree analysis. If the overall error probability calculated through THERP shows an unacceptable value, consideration on PIFs modification will be taken, in order to avoid the error to happen. The typical representation of this analysis suggested by Swain and Guttman takes a form of a tree, where the probability of failures or the HEPs is represented by its branches together with the likelihood of success in performing each step (Swain, et al., 1983).

Although considered as a powerful tool to predict and prevent human error, THERP has also its weaknesses that must be highlighted. The main limitation of this method is the analysis of contributing factors of human errors is not done structurally. This can lead to an identification of only a part of all possible errors relating to only certain numbers of performance influencing factors. Moreover, THERP emphasizes the errors that are usually found during operations in nuclear power plants, which indicates that the use of HEPs listed in the handbook for an analysis in process industries cannot be transferred one to one. Thus, an attempt had been made to improve the derivation of HEPs for THERP analysis in the process industries (Kariuki, 2007). Additionally, even though THERP proposes an implementation of HF analysis during plant design, the analysis result does not specifically point out the HF relevant design parameters that must be taken into consideration in preventing human errors from occurring during operation.

3. 3 Consideration of Human Error in HAZOP

The conventional HAZOP has been used in many domains and has gained wide acceptance. During the examination, issues concerning human error are nonetheless not systematically involved and scrutinized. It is undeniable that HAZOP can recognize human contribution in causing process deviation, yet merely arbitrarily. Human (Error) HAZOP was developed as an attempt to comprise human error issues that can arise hazards in a process plant (Kirwan, et al., 2001). Human HAZOP is initiated by using the result of hierarchical task analysis (HTA), which provides exhaustive descriptions of tasks within the process hierarchically. Guidewords are to be applied on the bottom level tasks from HTA. The next procedures are similar to classic HAZOP, using the following guidewords: ‘less than’, ‘more than’, ‘as well as’, ‘other than’, ‘repeated’, ‘sooner than’, ‘later than’, ‘mis-ordered’, and ‘part of’ (Stanton, et al., 2005).

Although Human HAZOP has included human error issues into safety analysis, this method still has drawbacks to be highlighted, especially in finding a systematic attempt to avoid human error and the incidents caused by it. These drawbacks are for instance:

- HAZOP and Human HAZOP focus only either on technical parts of the system or on human relevant tasks, and not on the entire system as a whole.
- Both HAZOP and Human HAZOP do not systematically consider the corrective action to be conducted if a hazard takes place. This can require operators to perform further actions where errors can still occur.
- Human HAZOP can identify possible human errors and their corresponding causes, but cannot comprehensively reveal the underlying causes why operators make errors.

- Without recognizing the real underlying causes, finding the optimal modifications or proposing the most necessary safeguards is very unlikely to be realizable.
- HAZOP and Human HAZOP cannot directly recognize if a disturbance was caused as an implication of incorrect operator action in other parts of the plant.

3. 4 HF in Process Plant Design

Performing HF analysis must be initiated as early as possible to be able to seize the system potential as a whole in preventing all possible errors and to avoid the needs of later changes. Consideration on HF must become one point of interest during plant design, since this is where the actual attempts to avoid human error must take place.

However, since performing HF analysis is momentarily not one of the main interests in process industries due to some reasoning; many people still see the incorporation of HF in process design sceptically. The sceptics look at the necessity to include HF during process design as extra burdens to the design team, since they believe that the performance of extra analyses in addition to the whole design activities can be unbearably laborious. Even without a HF analysis, a process design might never meet an optimal end, due to so many considerations that must be taken into account. Practitioners are convinced that many safety analyses have already comprised issues concerning human errors, and that performing these analyses during design will give more than adequate support to the design team. This way of thinking has directed practitioners to abandon the real intention of taking HF into account during process design, and to ignore the fact that not all of the commonly used safety analysis methods are applicable throughout the whole design phase.

Figure 3. 1 shows the applicability of several safety analysis methods (as mentioned earlier in Chapter 2.7) in different stages of process design, which in this example is described as the conceptual design, detailed engineering and construction/start-up. The figure shows, that only a few methods can be used in every design stage including the construction/start-up, among them are the checklist and what-if analysis (Heikkilä, 1999). However, although these methods are applicable for design phase, the implementation of a single method individually cannot adequately deliver necessary information required to optimally avoid human error. They need to be performed in

association with other methods to provide more comprehensive insights concerning HF issues in the design. The danger of it is that an analyst being unable to find the proper structure of the analysis and unsystematically implements those different techniques. The result obtained from such an analysis will only lead to false or irrelevant findings.

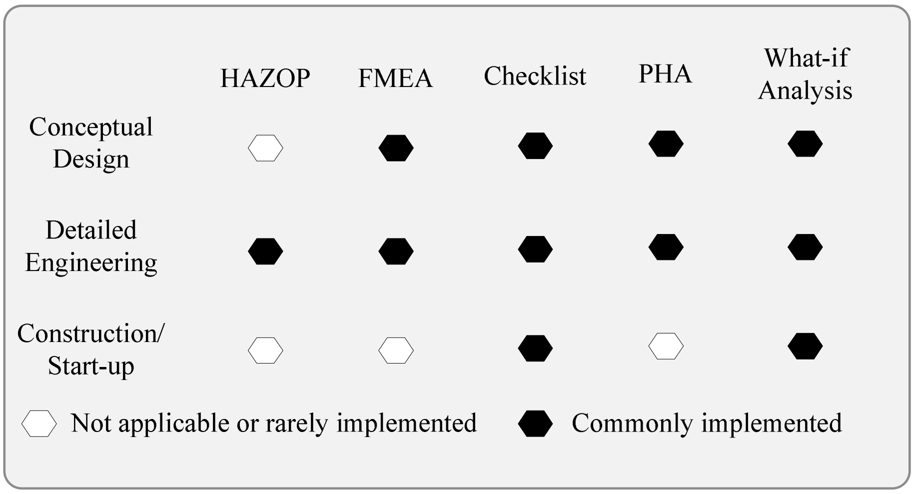

Figure 3. 1 Application of safety analysis methods on process design **(Heikkilä, 1999)**

3. 5 HF in Alarm Management and DCS-Design

HF in the context of alarm management and design of DCS is commonly interpreted as the design of human-system interface (HSI), which includes design of displays, different control elements and the general control room configuration. Since human information processing capacity plays an enormous role in the performance of supervisory tasks, the design of HSI must be able to ensure operator's situational awareness (SA), vigilance and workload to help them achieving a reliable decision making. Situation awareness (SA) is defined by Endsley as the operator's perception of what is happening within a certain time and place, their comprehension of the meaning, and in projecting its status in the near future. Vigilance on the other hand can be interpreted as "the capacity for sustained effective attention when monitoring a situation or display for critical signals, conditions or events, to which the observer must respond" and often referred to as alertness (Sandom, 2001).

There are several methods developed to assess and optimize operator SA and to assist decision-making process. Most of the methods consider human's perception processes, general cognitive ability and personality as the sources of SA. Other techniques provide a prediction about the level of operator SA in complex and dynamic systems, focusing more on the interaction between human and technical facility as an important source of SA. An example of such methods is the Situation Awareness Process Analysis Technique – SAPAT, which suggests the application of existing SA models to analyse interactive control system in order to identify the sources of SA and to analyse the hazardous interactions in the system (Sandom, 2001). This technique provides a way to deal with the design trade-off between usability and safety by suggesting design solutions from a system safety perspective based on HAZOP results (Noyes, et al., 2001).

In the area of human-system interface (HSI) design, many guidelines provide recommendations in optimizing the interaction between process and operating personnel, (O'Hara, et al., 2002). However, since the success in working with computers lies also on the user's knowledge concerning the system they are working with, designing HSI needs to include an analysis of the tasks from knowledge requirements perspective. Several methods to analyse knowledge intensive tasks in HSI were developed (Diaper, 1989), i.e. the Goals, Operators, Methods and Selection Rules (GOMS) – approach (John, et al., 1996). Those techniques provide a structured decomposition of tasks and can help the system designers to systemize the information provided to operators in such a way that facilitates their decision-making process.

Despite the availability of such methods, in process industry designing DCS is normally conducted after practical experiences and expert considerations. HF is normally included at the line end of the DCS design, where the design of HSI takes place. This late inclusion of HF considerations cannot optimally improve system safety, since incidents in computer controlled plants can be caused through many reasons other than inadequate design of HSI. Equipment failures or software faults, insufficient operator knowledge about the process, and system design failure due to the ignorance or misunderstanding reaction to the displayed information are the common problems that had caused disasters to happen (Kletz, et al., 1995). This indicates how each aspect of DCS design can address deficiencies of HF issues. Therefore, HF must be taken into consideration during early design of DCS, as early as the identification of alarms is taking place.

3. 6 The Need for Further Development of HF Methods

Despite the availability of different methods and techniques to analyse human errors, there is still a need for a systematic and clear-structured way to considering HF in the process industries. The HF methods discussed in this chapter, whether the qualitative or the quantitative ones have essential drawbacks that can fatally lead to a faulty result in understanding system weaknesses to comply with human limitations. Moreover, the available techniques in general have limited coverage in terms of their application. One technique can be implemented during a certain stage of plant design or operation, while another one applies only to other stages. None of the techniques provides a clear way to analyse and implement HF during the entire life of a plant. An approach that is applicable for design, construction, and plant operation as well as maintenance activities, which assists the analysis of both field and control room work and complies with both technical deficiencies as well as human limitations, must be available for an implementation in the process industries.

CHAPTER 4

MOTIVATION OF THE WORK

A computer-based method for HF analysis, PITOPA (the Process Industry Tool for Operator Action Analysis) was developed during a previous work for an analysis in existing process plants (Widiputri, 2007; Widiputri, et al., 2008). During this work, PITOPA had been optimised and validated several times in different types of process plants. After successful implementations of PITOPA, it came to the awareness that analysing HF only during process operation cannot optimally increase the quality of operator performance and plant safety, since the findings delivered through such an analysis often require major modifications on the plant, which is not always a feasible case. For this reason, PITOPA must be enhanced to such an extent to include HF considerations in the earliest phase of process plant design.

Due to the need to consider many issues during design of a process plant, many practitioners are convinced that adding HF into the design process will only result in a much bigger load without significant results. Nonetheless, since every goal a company is aiming can be obtained only if the operators are guaranteed their safety in work and understood in their limitations, there is no further option other than to design every aspect of the plant based on their requirements. If an adequate HF method that can link HF analysis with other important design issues is available, the sceptic looks on HF can be eliminated and providing the operators with an optimal working environment will become more achievable.

This work develops an approach for a systematic and comprehensive HF analysis of process plants that is applicable in both process design and plant operation. Since it obliges much more than only a modification of different available methods to incorporate HF analysis into a design process; a careful consideration to structure the development of such approach is required. In the context of bridging HF consideration in every activity during design process, an integration of HF into general safety analysis is an essential matter. The attempt to achieve a safer operation must include the consideration that technical aspects affect human beings in a great manner, and also the other way around, that errors executed by operators can lead to later technical problems. For this reason, integration between HF analysis and the general safety analysis, such as HAZOP studies must be enabled.

To comprehensively design a system that ensures the conformance to different operators' requirements, HF analysis must be able to comprise the whole operators' activities during process operation, either the works to be conducted on-site (field works) or works to be conducted in control rooms/centres (monitoring and supervisory control). In terms of providing support for control room operators, HF must be incorporated into alarm management and into the design of DCS. Often, the design of control and alarm system is taken as pure engineering matters. The inclusion of HF always starts at latest design stages, during the design of HSI, which is already too late. HF should have been considered as early as alarms are being identified and configured, and not later than the rationalization stage. Therefore, the HF method developed here must be able to specifically address the inclusion of HF into alarm management and into DCS design.

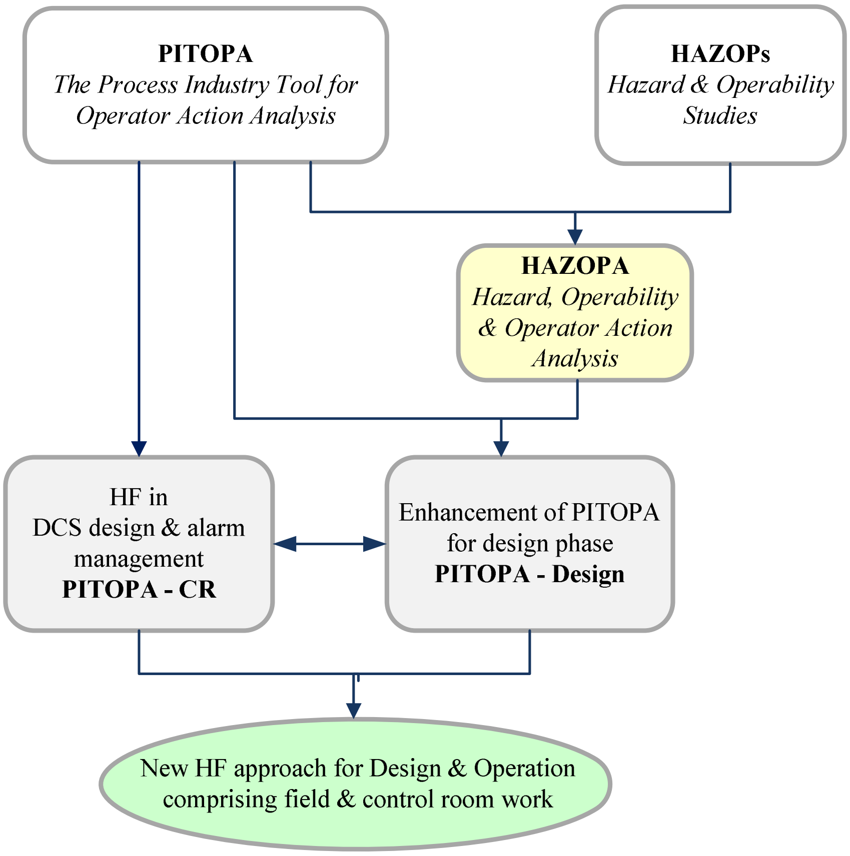

Figure 4. 1 Structure of the development of the new HF approach

The new approach developed in this work will provide a structured and systematic means to perform HF analysis concurrently with other different analyses and design activities, and will be additionally applicable for an analysis during process operation. Analysis of operator actions and their requirements in performing both manual/field works and control room works are comprised in the new developed approach. The development is illustrated in Figure 4. 1 and takes into account of the following main points:

1. the inclusion of HF consideration into plant design,
2. an integration between HF analysis and a widely implemented general safety analysis during design of process plants to provide a way to meeting regulation requirements in designing process plants,
3. an enhancement of the existing HF analysis methods to provide a systematic way in analysing control room work/supervisory control, and
4. since designing DCS and alarm system influences the work of operator in a significant manner, especially in highly automated systems, a technique to incorporate HF into alarm management and into the design of DCS must be additionally provided.

CHAPTER 5

PROCESS INDUSTRY TOOL FOR OPERATOR ACTIONS ANALYSIS (PITOPA)

Performing a HF analysis in process industry without a systematic means can become very lengthy and laborious. For this reason, a new approach, the Process Industry Tool for Operator Actions Analysis (PITOPA) was developed (Löwe, et al., 2007). The development of PITOPA as demonstrated in Figure 5. 1, involved the implementation of three HF techniques; a task analysis (TA), the Operator Actions Analysis (OAA) technique and an evaluation of performance influencing factors (PIFs). In order to ease the application of the new method and to facilitate the documentation of the huge amount of information collected during analysis, PITOPA was computerized and linked with a database system.

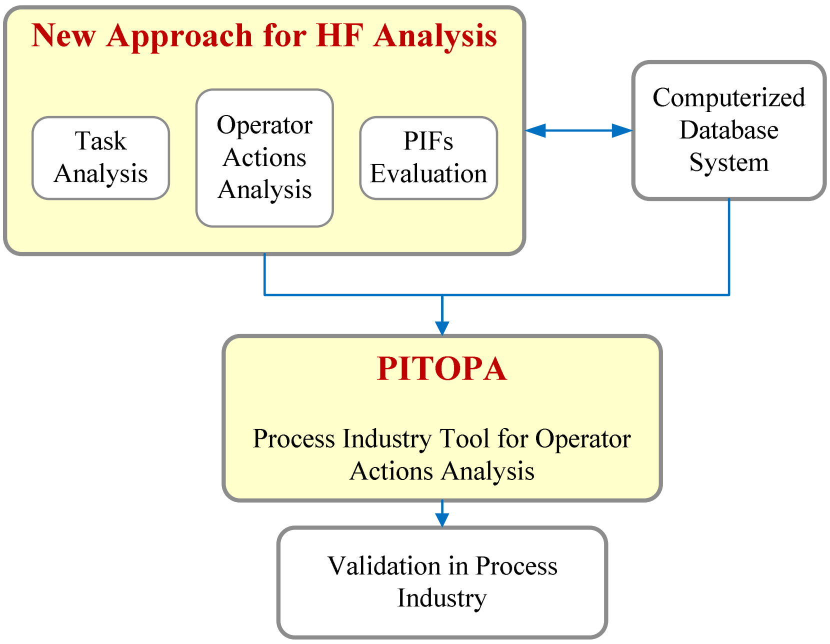

Figure 5. 1 Development of PITOPA

Figure 5. 2 demonstrates the systematic structure in implementing the new method PITOPA. By making use of the available process information and documentation such as the process flow diagrams, P&IDs, plans of plant layout, safety and near-misses reports, operating manuals and instructions, as well as the working procedures, a task analysis

must take place as an initial step of the whole analysis process. The aim of TA is to collect as much as possible understandings about the process under analysis, and to identify the required human operator's contribution during operation. At the beginning of the analysis, the system is broken down into smaller parts and functions. Operator tasks are then analysed in their relation to each part of the process in achieving the function's intended purpose.

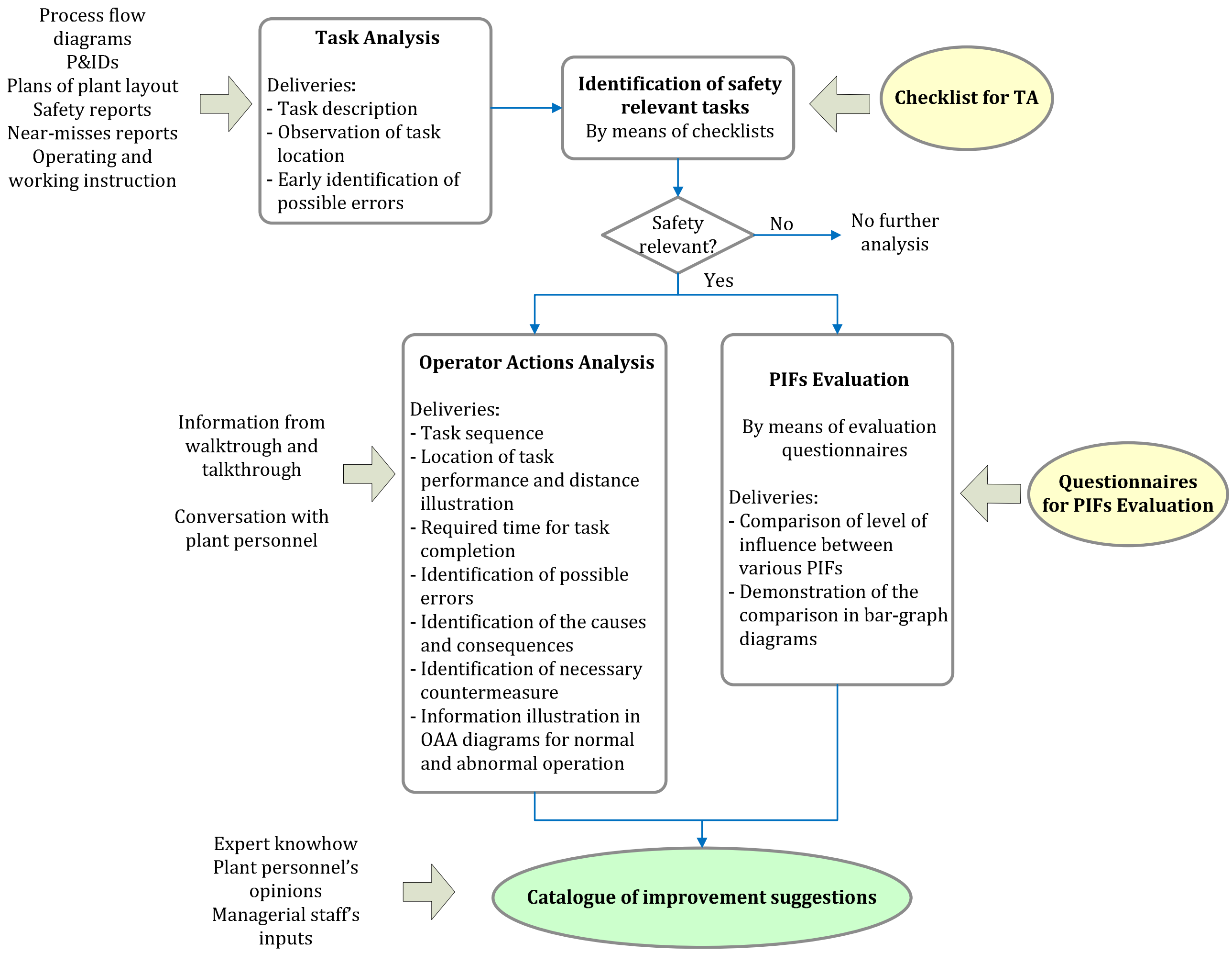

Figure 5. 2 Performance of PITOPA

The analysis of operator tasks is aimed at the early recognition of requirements on operators and particular constraints caused by extreme working and environmental conditions. If during the performance of certain tasks, harms to the operators might arise, these tasks are to be considered as safety relevant or critical. The harms to be considered can be a direct contact with chemicals, exposure to heated equipments, or awkward positioning that can with time cause permanent injuries to the operators. Besides the dangerousness, identifying safety relevant and critical tasks requires considerations about task complexity and difficulty, as well as the physical load caused through the performance of those tasks. The determination of safety relevant tasks is facilitated by a checklist (Figure 5. 3). If at least two of the three options: complex/difficult, physically hard and dangerous were chosen to characterise a certain task, than this task will be considered as safety relevant.

On all of the identified safety relevant/critical tasks, further analyses are required, since during the performance of these particular tasks, error occurrence must be strictly avoided. PITOPA provides two techniques to analyse these tasks further, which are the Operator Actions Analysis (OAA) and the PIFs evaluation techniques. In the following section, both techniques are described in more detail.

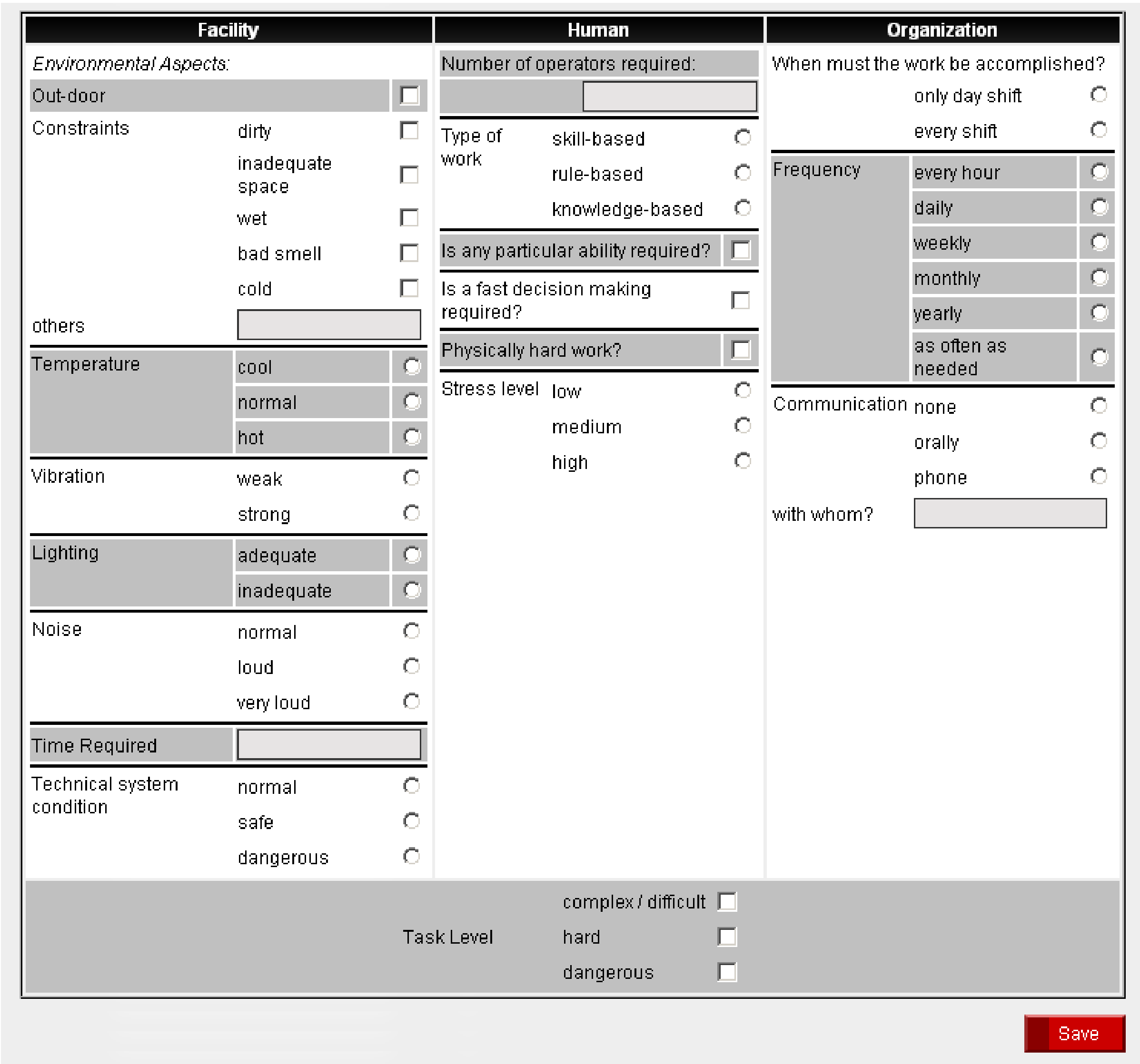

Figure 5. 3 Check list for task analysis to determine the safety relevant tasks

5.1 The New Technique for Operator Actions Analysis (OAA)

The new operator actions analysis (OAA) provides a way to evaluate the consequences of incorrect or omitted actions during task performance in both normal and abnormal operation. For this purpose, distance between components in the system which have to be operated simultaneously must be evaluated, since distance can help determining load on operator during task performance. Identified tasks are decomposed into subtasks or steps to understand their sequence. Analysis of every step includes the identification of location and time span of the performance, possible errors, error causes and consequences as well as the necessary corrective actions by operators. Figure 5. 4 demonstrates the OAA diagram for a normal operation as one result of OAA. Each step in the task sequence is represented using a numbered rectangle in the diagram. The x-axis of the diagram represents time span, while the y-axis shows the distance between equipment that need to be operated simultaneously. The horizontal lines parallel to x-axis indicate the grade levels, on which each step has to be performed (Dalijono, et al., 2005). Whenever due to inadequacy of plant layout, accessibility, or time available, an overlapping of tasks or other kinds of work overloading is recognized, incorrect actions are becoming more likely, which can subsequently cause disturbances leading to abnormal situations.

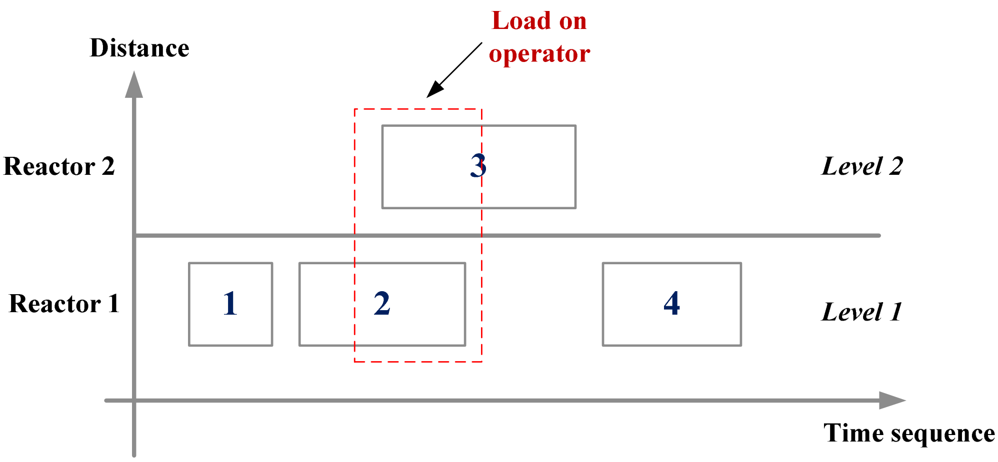

Figure 5. 4 Operator Action Analysis Diagram for Normal Operation

An abnormal operation that follows an error will require some corrective actions as the attempt to bring the process back to its normal operating state. During such abnormal situation, an operator has to respond to a disturbance while at the same time has to keep performing the normal tasks. This can significantly affect their performance and can once again result in errors. Figure 5. 5 demonstrates an abnormal OAA diagram (Dalijono, et al., 2005). The structure of the diagram is similar to the one for normal operations; but underneath the x-axis, the disturbances, their consequences and the necessary corrective actions are illustrated.

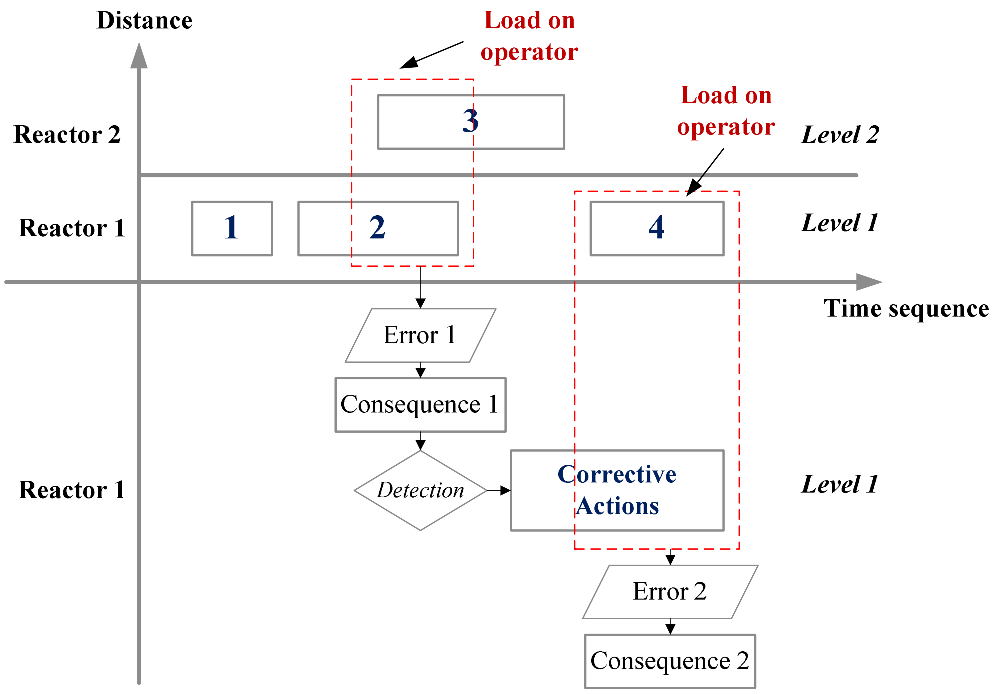

Figure 5. 5 Operator Action Analysis Diagram for Abnormal Operation

Performing OAA on each of the identified safety relevant tasks in both normal and abnormal operation enables:

- Identification of every step to successfully complete one task.
- Recognition of inadequacy in plant layout and job design.
- Identification of possible errors during the performance of each step, and the consequences thereof.
- Identification of necessary corrective actions following each error.

5.2 Technique for Performance Influencing Factors (PIFs) Evaluation

Working environment must be configured in such a way that best suits human beings during their work. Due to the complex interaction between various factors within a man-machine system, it becomes very complicated to settle on the factors that can contribute in improving the whole system. The technique for PIFs evaluation enables the determination of the most influencing factors on operators during a certain task performance. By means of this technique, improvement potentials to optimize process safety can be systematically revealed.

Table 5. 1 PIFs classification and relative weights

HF Group	PIF	Attribute	Global weight
Technical Facilities	Equipment	Technical equipment	***0.0183***
		Process safety condition	***0.0061***
	System Interface	Display	***0.0400***
		Communication system	***0.0447***
		Feedback and alarm	***0.0141***
	Environment	Lighting	***0.0209***
		Temperature	***0.0233***
		Vibration & noise	***0.0185***
		Air quality	***0.0281***
	Workplace Design	Layout	***0.0580***
		Accessibility	***0.0613***
Human	Skill & Knowledge	Type of task	***0.0451***
		Qualification & experience	***0.0977***
	Manual & Physical Handling	Physical load	***0.0754***
		Additional tools	***0.0675***
	Stress Level	Concentration demand	***0.0191***
		Monotony	***0.0109***
		Health hazards	***0.0176***
Management System	Job Design	Task frequency	***0.0172***
		Job description	***0.0861***
	Line Management & Instruction	Line of responsibilities	***0.0446***
		Procedures	***0.0409***
		Supervision	***0.0446***
	Information	Labels & signs	***0.0192***
		Communication	***0.0532***
		Documentation	***0.0276***

For this evaluation, PIFs are classified into three HF groups as discussed in Chapter 2 (technical facilities, management system and human/people). For the evaluation purpose, the factors within each group are decomposed into smaller attributes. The influence of one HF group on operator during a certain task is determined through the contribution of each PIF within it. Likewise, the influence of each PIF is determined by each attribute contributing to it. The contribution of PIFs and/or attributes in affecting operator performance can be referred to as the importance level, and will be determined by eliciting weights (Table 5. 1) using the Analytical Hierarchy Process (Saaty, 1980). The weights represent the importance of one factor in giving influence on operator's work and performance, compared to other factors in the same weighting system

(Widiputri, et al., 2008). The elicitation of weights for this evaluation involved a European-wide industrial survey (PRISM, 2004).

However, although the weights represent the potential and importance of every factor and attribute in influencing human performance, the actual level of influence depends strongly on the situations and specific characteristics of every task. Hence, the quality of each PIF in affecting human at the time the analysis takes place must be evaluated by using scores/rating (Figure 5. 6) that will characterise demands on operators during performance of safety critical tasks. A questionnaire is available to assist the scoring process (Widiputri, 2007).

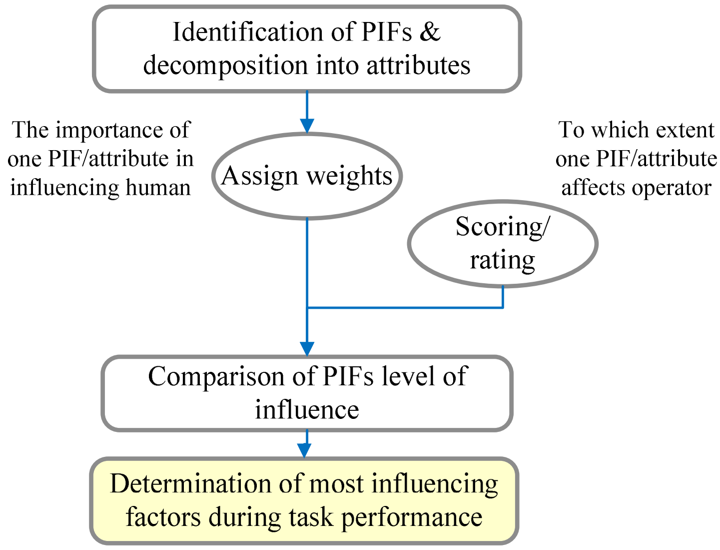

Figure 5. 6 Determination of most influencing factors

In this rating, the score '1' is used to represent an extremely good adequacy of a PIF in supporting human and in reverse, '10' will represent an extremely poor quality. In other perspective, score 1 is given to those PIFs that are either providing adequate support to operators or totally irrelevant for the task performance, so that no improvement must be made to the corresponding PIF (Löwe, et al., 2007). Ultimately, the influence level comparison is made based upon both the weight and the score assigned to each PIF during the performance of a certain task (Figure 5. 6).

5.3 Validation of PITOPA in the Process Industry

The performance of HF analyses by means of the new PITOPA at BayerCropscience AG in Germany has delivered numerous benefits (Löwe, et al., 2008). The company and the management received many insights concerning the plant condition from operators' perspective. Although it can be ensured that plant managers and engineers understand every little detail concerning the process, operators are still the ones who know exactly the plant's strengths and weaknesses regarding to how various aspects are affecting them during their work.

The validation of PITOPA at this company revealed that there are a lot of discrepancies between the opinions of operators and the managerial staffs and engineers in viewing the importance of different PIFs in supporting operators work. Several typical problems that reflect the misapprehension between these two groups are for instance:

- **Working procedures** that are not anymore up-to date. Due to many changes and plant modifications, working space might be reduced, or equipments are dislocated. After one minor modification it might be too exhausting to make changes on the working procedures, so people tend to ignore it. But after several minor modifications, it becomes very likely that the working procedure no longer suits the actual plant conditions. Operators are often left with a single option that is to adapt with the new plant condition and to creatively modify the way they work to adjust to the situation. Although most of the times such phenomenon is harmless and even desired, there is a huge danger behind it that can act as a latent condition and can lead to a disaster.

- **Proper documentation** and journals are for the operators, especially those who work on shifts, a very essential matter. Such journals provide the operators with necessary information before they start working and help maintaining their situational awareness concerning process condition. The managements views this matter also as an important thing, but not as important as a good supervision and good line management.

- **Extreme environmental condition** might be the most typical aspect that receives different level of appreciation from operators and management, especially in those less automated plants where a great deal of manual handlings needs to be conducted. With the assumption that operators have a vast capability to adjust with their surroundings, many engineers and managerial staffs do not see the urge to provide operators with more comfort during their work.

- **Additional supporting tools** are sometimes introduced as an apology for an inappropriate working condition or working environment. This is quite typical in cases where operators must conduct tasks that require extra physical strengths or other tasks, during which contacts to dangerous substances might arise. The use of additional tools can often lead to even more extra load, if their availability is not properly arranged to give the exact support the operators require.

- **Signage and labelling.** These two issues might seem to be very trivial and many believe that signage and labelling must have been provided in a good and adequate manner. However in the reality, problems with signs and labels can be often found in existing plants, especially if the plant had been operating for many years and has experienced numerous modifications during the years. Signs placed in reverse or labels that are not readable anymore can contribute as a latent condition that can force operators to execute incorrect action.

Therefore, the performance of HF analysis must include operators' opinion concerning how they feel affected through different aspects within the system. With this understanding, it will be possible to correspondingly recognize the necessary improvement to be introduced upon the existing plants, in order to better support operators in their work so that errors can be prevented. The new computer-based PITOPA in this context provides the company with a systematic means to comprehensively understand the state of plant conditions from HF perspectives, the underlying problems that might result in operator errors, the possible errors that can occur and their consequences, to anticipate the necessary corrective measures in overcoming with the error consequences, to comprehend the operators requirements and eventually to reveal the most necessary improvements to be made on the whole system. An example of the PIFs' importance level comparison as one of the outcomes of PITOPA is shown in Figure 5. 7. Another extra benefit delivered by the performance of HF analysis is the general improvement in operators' motivation, since they become aware; that their needs and requirements are being taken into account in the company's safety policy. This will as a result lead to an integrally healthier working atmosphere.

The validation of PITOPA in process plants has on the other hand recognized the necessity to enhance the technique into an approach that comprises a broader spectrum of analysis. PITOPA was found to be suitable for HF analysis in chemical plants with relative big portion of manual/field work, or in other words is implementable for analysing HF quality of less-automated plants. The analysis of work in control room by means of PITOPA will not deliver comprehensive solutions in overcoming with problems in control system and control room configuration in general. Moreover, due to the amount of required information during the analysis, PITOPA is mostly applicable to analyse work in existing plants, or in processes that are already running in operation. PITOPA is for this reason not necessarily suitable to be implemented during early design phase of chemical process plants.

Attribute Name	Statistics
Physical Load	7.49%
Qualification & Experience	6.79%
Job Description	6.15%
Supervision	4.55%
Accessibility	4.25%
Tools	4.01%
Communication System	3.54%
Lay-out	3.45%
Procedures	2.91%
Communication	2.71%
Display	1.80%
Type of Task	1.79%
Task Frequency	1.58%
Concentration Demand	1.49%
Documentation	1.41%
Labels and Signs	1.37%
Technical System	1.09%
Line of Responsibilities	0.91%
Feed-back and Alarm	0.64%
Monotony	0.53%
Process Safety Condition	0.18%
Vibration and Noise	0.00%
Lighting	0.00%
Temperature	0.00%
Air Quality	0.00%
Health Hazards	0.00%

PIF Name	Statistics
Manual & Physical Handling	11.34%
Job Design	8.43%
Line Management & Instruction	8.40%
Skill & Knowledge	7.80%
Workplace Design	7.68%
Information	5.78%
System Interface	5.57%
Stress Level	2.01%
Environment Aspects	1.80%
Equipment	1.09%

Group Name	Statistics
Management	22.10%
Human	18.86%
Facilities	13.50%

Figure 5. 7 Example of PIFs comparison delivered by PITOPA

CHAPTER 6

EXTENDING HAZOP TO INTEGRATE HF INTO GENERAL SAFETY ANALYSIS

The performance of qualitative safety analysis in process industry has become a regulated requirement in some countries, which these days is mainly facilitated by HAZOP. HAZOP enables the identification of all design intentions of every part of the system, and by means of using guide-words, also indicate the possible deviations of process parameters and consequences that might arise (Crowl, et al., 2001). HAZOP also attempts to find the causes why deviations are possible, so that as a result, safeguards to avoid such events from occurring can be proposed (see also chapter 3.3).

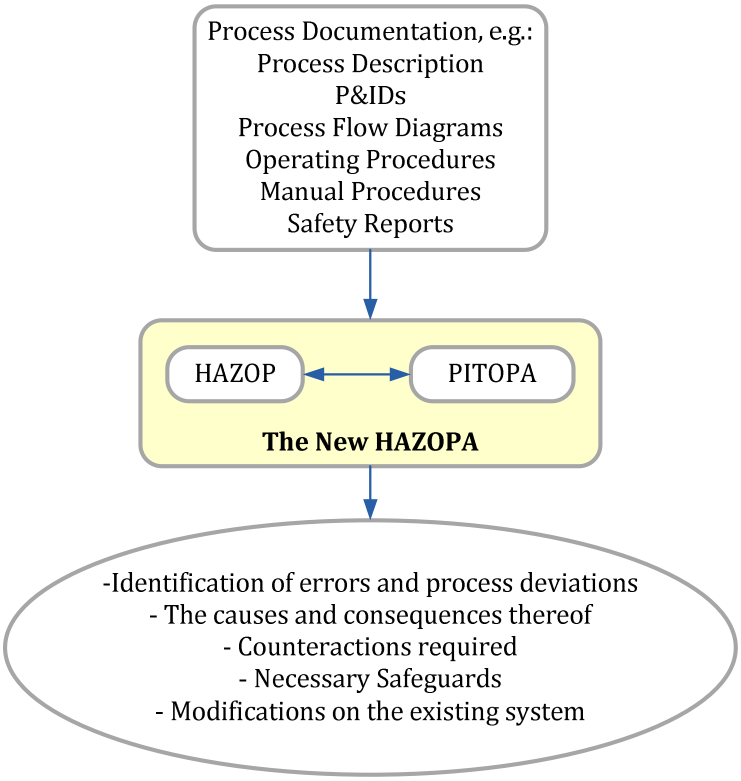

Figure 6. 1 The new Hazard, Operability and Operator Actions Analysis (HAZOPA)

By integrating PITOPA into HAZOP, it will be possible to systematically observe both technical failures and human errors that could occur during operation. PITOPA enables the identification of task sequences and the most influencing factors that can possibly add workload on operators during task performance. By recognizing these issues, possible errors can be predicted and the consequences of these errors can be anticipated. Hence, with PITOPA any possible error that can likely lead to parameter deviations will be recognizable. This information will extend the results coming from HAZOP to systematically identify all deviations including those that are caused by operators. Reversely, if HAZOP already indicates that some deviations could have been occurred through operator involvement, PITOPA will analyse further the reason why operator conducts this particular incorrect action. At the end of the analysis, every source of failure will be revealed; either it is pure technical or HF relevant. This way, the most underlying causes of parameters deviations can be determined, so that discovering extra safeguards to avoiding them from happening will be achievable.

6.1 Development of HAZOPA (The Hazard, Operability and Operator Actions Analysis)

The integration between general safety and HF analyses into one systematic means is realized through the development of HAZOPA (The Hazard, Operability and Operator Actions Analysis). HAZOPA combines the powerful method for qualitative safety analysis, HAZOP studies and the new systematic HF analysis method, PITOPA (Widiputri, et al., 2009). By utilizing the available process documentation such as process description, P&IDs, process flow diagrams, operating manuals and procedures, as well as safety reports, the new HAZOPA will enable the identification of:

1. both possible process deviations and human errors
2. the causes and consequences thereof
3. the interrelation between errors and parameters deviations
4. required corrective actions both following parameter deviations and incorrect actions
5. the necessary safeguards and countermeasures, and
6. the necessary modifications of the existing system.

The structure of HAZOPA (Figure 6. 2) is similar to PITOPA. This new approach is an extension of PITOPA with a specific benefit that it takes into account not only the HF aspects but also the technical ones, based on the results coming from HAZOPs. A proper and ideal implementation of this new means HAZOPA will eliminate the need to perform HF and safety analyses separately and repetitively. Moreover, the results will provide more comprehensive understandings concerning the interrelation between the technical systems and human operators.

The implementation of HAZOPA (Figure 6. 3) starts with a process description and identification of parts within it, followed by the identification of process nodes. The next step of the analysis will be differentiated in two dimensions, the HAZOP part and the task analysis part. Both analyses will run simultaneously for each process node. In the HAZOP part, the intervention of human operators in causing parameter deviations needs to be identified. In addition to it, for every parameter deviation, either if it was caused by incorrect operator action or not, the necessity of any corrective action by operators must be identified.

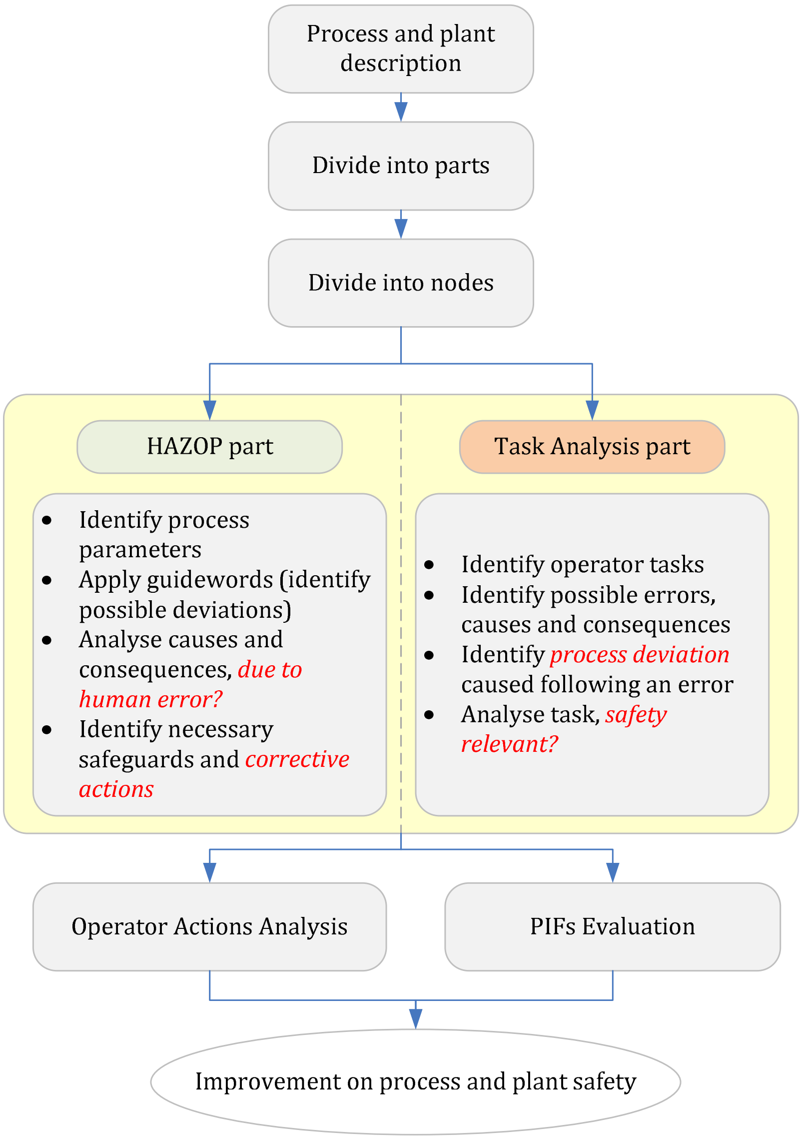

Figure 6. 2 Structure of HAZOPA

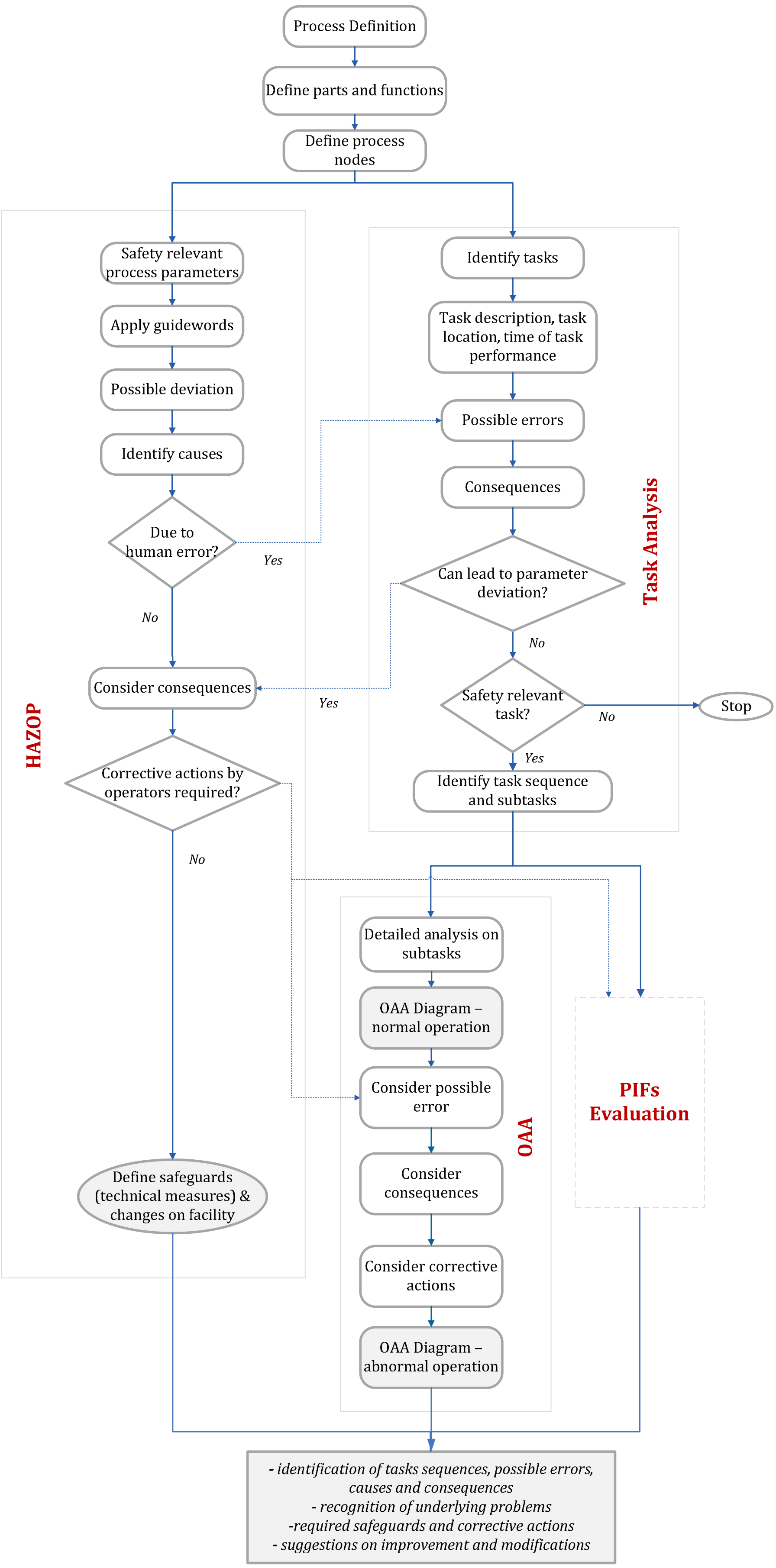

Figure 6. 3 Steps to perform HAZOPA

In the task analysis part, all operator tasks in relation to every process node are identified. Following this step, all possible errors, the causes as well as the consequences will be identified as well. In addition to a classic task analysis, the possible process deviations caused by operator incorrect action must be specifically identified. Afterwards, through a careful consideration on the task characteristics, the safety relevant tasks are identified. A worksheet for this purpose is available in Figure 6. 4 below.

After the most important part of the analysis had taken place, on each identified safety relevant/critical task and crucial process deviations, operator actions analysis and PIFs evaluation are conducted. Through the implementation of both task analysis and HAZOP at the same time for a certain process node, it will be possible to recognize the susceptible interface between the technical system and operators where incorrect actions can lead to further disturbances. Moreover, it will also be possible to determine whether error in one process part can relate to disturbances in other parts of the plant. By gaining awareness of these areas, a comprehensive solution to avoid errors and disturbances to happen will be achievable.

Process Node	Parameter	Possible Deviation	Cause	Human Involvement	Consequence	Corrective Actions	Safeguards	Remarks
				HAZOP Part				

	Identified Tasks	Location	Possible Error	Consequence	Can lead to process deviation?	Safety Relevant?	Remarks
				Task Analysis Part			

Figure 6. 4 HAZOPA worksheet

6.2 Case Study

In order to better understand the implementation of HAZOPA, in this subchapter a hypothetical case-study will be analysed as an example.

I. Process description

In this case study a simple mixing process is taken to be analysed with HAZOPA. The mixing process involves no chemical reaction and runs in batch. The whole process plant was designed for production of different types of chemicals, depending on market demands and production plans. However, since during mixing there is no reaction taking place, the analysis in this case study will ignore the type of chemical being produced at the time of the analysis. This mixing process requires both manual and automatic charging of both liquid and solid materials. The process diagram of the mixing process is shown in a simplified form in Figure 6. 5.

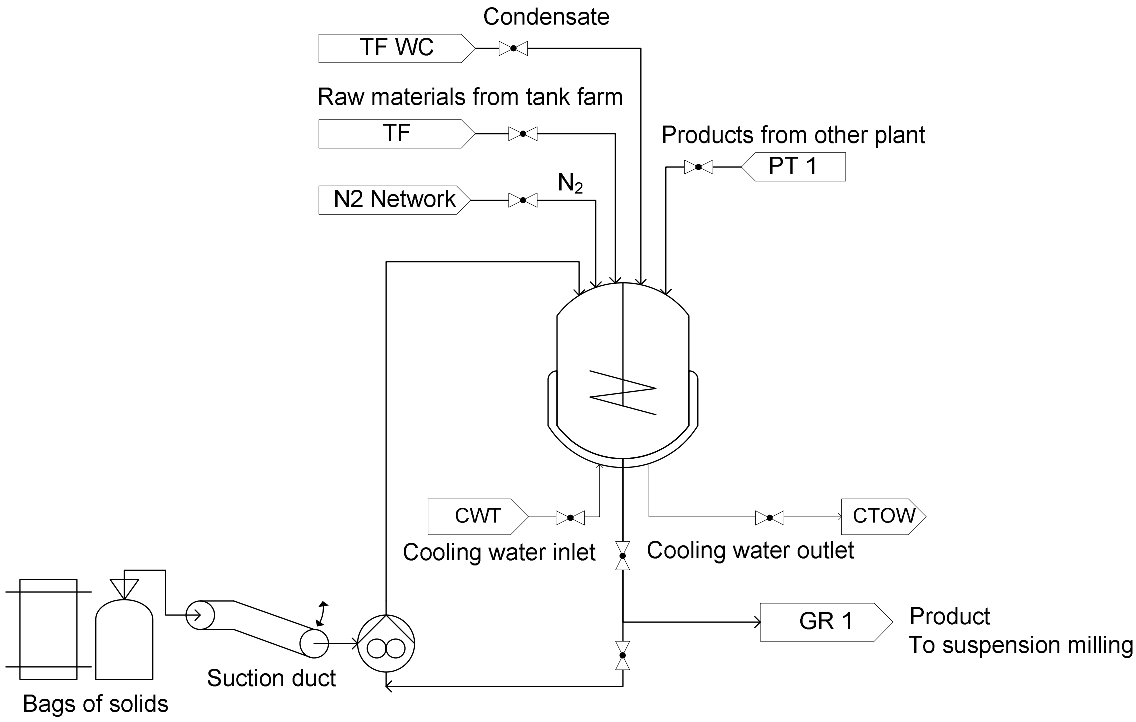

Figure 6. 5 Simplified process diagram of the mixing process

II. Division of the process into smaller parts and into nodes

The process demonstrated in Figure 6. 5 is to be broken down into smaller process parts, and furthermore into process nodes to provide a better analysis on the process. In this example, the process can be divided into 5 main parts as listed in Table 6. 1 together with their associated nodes.

Table 6. 1 Identification of process parts and nodes of the mixing process

Process Parts		*Process Nodes*	
P1	Charging of solid materials	**N 1.1**	Solid materials charging chamber – suction duct
P2	Charging of liquids	**N 2.1**	Liquid charging duct
P3	Pre-treatment of additives & solvents	**N 3.1**	Heating cabinet
		N 3.2	Solvent feed-tank (buffer tank)
P4	Mixing	**N 4.1**	Stir tank
P5	Suspension grinding	**N 5.1**	Grinder

III. The simultaneous and iterative performance of HAZOP and task analysis

To demonstrate the performance of both HAZOP and task analysis, 2 process nodes are taken as examples. The first node to be analysed is the P1.N1.1, which is the charging of solid materials that takes account of the operation of the suction chamber and suction duct. The next process node to be analysed is the P4.N4.1, the stir tank where the mixing process is taking place. The worksheets in Table 6. 2 and Table 6. 3 show the analysis of both process nodes.

P1.N1.1: Manual charging of solid materials

In this mixing process several types of solid materials must be added into the tank manually, through a suction chamber. The amount of these solids and in which size the bags are delivered by suppliers varies significantly.

P4.N4.1: Mixing process in a stir tank

The mixing process is conducted in batch, after the required amount of solids and liquid materials have been completely charged into the tank. To begin and during the process, several process parameters must be monitored and checked upon.

Table 6. 2 Analysis of P1.N1.1: manual charging of solid materials into charging chamber and suction duct

Process Node	Parameter	Possible Deviation	Cause	*Human Involvement*	Consequence	*Corrective Actions*	Safeguards	Remarks
P1 N1.1 Solid charging chamber - Suction duct	1. Temperature	Too high	Plugging in roller crusher	*Not identified*	Thermal product decomposition Production delay	*Yes*		Dismantlement of crusher following this event

Process Node	Identified Tasks	Location	Possible Error	Consequence	*Can lead to process deviation?*	*Safety Relevant?*	Remarks
P1 N1.1 Solid charging chamber - Suction duct	T1. Transporting solid materials from warehouse and arrange them on location	Warehouse and 1^{st} level	Selection and preparation of wrong solid materials	If acknowledged: Production delay If not acknowledged: Quality failure			
	T2. Charging solid materials in bags into chamber/ duct manually	1^{st} level	Incorrectly conducted	Injury Production delay		*Yes*	

Table 6. 2 and Table 6. 3 demonstrate the performance of HAZOP together with task analysis simultaneously on the two process nodes described earlier. At the beginning of the analysis, it is very likely that not all information can be thought of or recognized, since the nodes are interconnected one with another, so that to have a comprehensive analysis, this step must be done iteratively. As an example, the tasks to be conducted at the node P1.N1.1 (Table 6. 2) are not identified as to be able to cause process deviation at the beginning. However, as the analysis proceeds to the node P4.N4.1 (Table 6. 3), by taking a closer look at 2 of the causes of process deviations 4.1.3 (incorrect product composition), which are:

Cause 1 : feeding a wrong amount of materials into the tank

Cause 2 : selecting and charging the wrong kinds of solid materials

it is found that these causes are interrelated with errors by operators in other parts of the process plant. Both of the causes of deviation on product composition listed above resulted from the errors executed during the performance of manual charging of solid materials (node P1.N1.1, during both task 1.1.T1 and task 1.1.T2). Therefore, at this point, the initial analysis of node P1.N1.1 can now be completed by putting more information concerning the possible process deviations caused through error occurrence (Table 6. 4).

Table 6. 3 Analysis of P4.N4.1: mixing process in the stir tank

Process Node	Parameter	Possible Deviation	Cause	*Human Involvement*	Consequence	*Corrective Actions*	Safeguards	Remarks
P4 N4.1 Mixing process in stir tank	1. Pressure	Too high	Jam in the circulation pipeline to/ from the grinder	*Not identified*	Material release due to pipelines break-down	*Yes*	Flow control	
	2. Temperature	Too high	Excessive energy input through stirrer	*Not identified*	Product thermal decomposition		Temperature control in the stir tank	
	3. Product composition	Incorrect	1. Wrong amount of materials fed	*Yes*	Development of flammable atmosphere	*Yes*	Take-over accordance to check-lists	Corrective actions under supervision
			2. Wrong solid materials selected and charged	*Yes*	Quality failure	*Yes*	Updated working manuals	Corrective actions under supervision
			3. Wrong composition of liquid additives prepared	*Yes*	Quality failure	*Yes*	Updated working manuals	Corrective actions under supervision
	4. Tank level	Too high	Level measure-ment defect	*Yes*	Tank overflow	*Yes*	Redundancy, Cross-check by field operator	

Identified Tasks	Location	Possible Error	Consequence	*Can lead to process deviation?*	*Safety Relevant?*	Remarks
T1. Monitoring tank temperature and pressure	Control room				*Yes*	Conducted by control room operator
T2. Monitoring fluid level	3rd level	Not conducted	Tank overflow	*Yes (if not acknowledged by control room operator)*		Double checking through level indicator monitored in control room
		Incorrectly conducted	Inhalation of or contact with hazardous chemicals		*Yes*	Monitoring through sight glass is often hindered. Operators often open manhole to ensure materials flow and tank level
T3. Ensuring materials flow into the tank	3rd level	Not conducted Incorrectly conducted	Inhalation of or contact with hazardous chemicals	*Yes (if not acknowledged by control room operator)*	*Yes*	Monitoring through sight glass is often hindered. Operators often open manhole to ensure materials flow and tank level

Table 6. 4 Complete Analysis of P1.N1.1

Process Node	Parameter	Possible Deviation	Cause	*Human Involvement*	Consequence	*Corrective Actions*	Safeguards	Remarks
P1 N1.1 Solid charging chamber - Suction duct	1. Temperature	Too high	Plugging in roller crusher	*Not identified*	Thermal product decomposition Production delay	*Yes*		Dismantlement of crusher following this event
	Identified Tasks	Location	Possible Error	Consequence	*Can lead to process deviation?*	*Safety Relevant?*	Remarks	
	T1. Transporting solid materials from warehouse and arrange them on location	Warehouse and 1st level	Selection and preparation of wrong solid materials	If acknowledged: Production delay If not acknowledged: Quality failure	*Yes* *Process Deviation 4.3.1 (cause 2)*			
	T2. Charging solid materials in bags into chamber/ duct manually	1st level	Incorrectly conducted	Injury Production delay	*Yes* *Process Deviation 4.3.1 (cause 1)*	*Yes*		

IV. Determination of critical tasks and identification of necessary corrective action

After every identified node is iteratively analyzed through the combination of HAZOP and task analysis, the next step will be to summarize all the recognized critical tasks. Critical tasks in this context are defined as all tasks, which can cause process deviations if not conducted as intended, and tasks that are considered as safety relevant. The determination of these critical tasks will serve as a filter before continuing to further analyses. Only tasks with perceived criticality are to be analyzed in-depth through the operator actions analysis and PIFs evaluation. For the case-study discussed in this chapter, the identified critical tasks at node P1.N1.1 and P4.N4.1 are tabulated in Table 6. 5.

Besides the determination of different critical tasks during plant operation, the necessary operator contribution in coping with unexpected disturbances can also be delivered through the iterative analysis. Table 6. 6 lists all points where operator corrective actions are required following a parameter deviation or an operator error. This recognition of necessary operator's involvement to remedy process disturbances is very crucial. The necessary corrective actions will then be as well analyzed further through the operator actions analysis, together with the identified critical tasks.

Table 6. 5 List of tasks with perceived criticality at node P1.N1.1 and P4.N4.1

Task Nr.	*Task Description*	*Process Deviation Caused*	*Safety Relevant*
1.1.T1	Transporting materials from the warehouse	**Deviation 4.1.3 (cause 2)**	
1.1.T2	Charging solid materials in bags into suction chamber/duct manually	**Deviation 4.1.3 (cause 1)**	√
4.1.T2	Monitoring fluid level in the stir tank	**Deviation 4.1.4**	√
4.1.T3	Ensuring flow of materials into the stir tank		√

Table 6. 6 Identification of deviations in need of operator corrective actions

Process Part		*Process Node*		*Deviation and Causes Requiring Operator Corrective Actions*	
P1	Charging of solid materials	**N1.1**	Solid charging chamber – suction duct	**1.1.1**	Temperature too high, caused by plugging in the roller crusher
P4	Mixing process	**N4.1**	Stir tank	**4.1.1**	Pressure too high, caused by a jam in the recirculation pipeline
				4.1.3 (cause 1)	Failure on product composition, caused by mistake in controlling the amount of materials fed
				4.1.3. (cause 2)	Failure on product composition, mistake in preparing solid materials
				4.1.3 (cause 3)	Failure on product composition, mistake in preparing additives

V. The Operator Actions Analysis step

For all identified critical tasks (all tasks listed in Table 6. 5), OAA is to be conducted. In addition to it, the necessary corrective actions following process disturbances (Table 6. 6) are to be defined and analyzed by means of the same technique. The similar steps as in the classic operator actions analysis (chapter 5.1) are performed to identify further the characteristics of work to be completed by operators. Through this operator actions analysis, it will be possible to see in more detail the possible incorrect actions that operators might conduct under inadequate working condition, and what impact these errors have on the operation.

For further analysis of the case study, one critical task will be discussed here. Taken as example is the task 1.1.T2, which is the manual charging of solid materials in bags into the charging chamber. To complete this task, 4 subtasks or steps must be done in a certain sequence. The analysis of the completion of this task in a normal operation is demonstrated in Table 6. 7 and Figure 6. 6.

Table 6. 7 Operator actions analysis on task 1.1.T2: “Charging solid materials into charging chamber manually”

Nr.	***Location***	***Step***	***Possible Error***	***Conse-quence***	***Time Required (min)***	***Remarks***
1.	1st level	Switching on the suction pump, roller-crusher, and exhaust	Not done	Process delay	2 min	
2.	1st level	Placing the solid materials in bags approaching the chamber	Incorrectly done	Process delay, injury	6 min	Inadequate space for maneuvering
3.	1st level	Placing bag on the sieve (grid), opening it by using a knife, and pouring the content down the chamber	Incorrectly done	Material release, dust formation and explosion, injury	40 – 60 min	Physically hard work, weight of each bag can reach 25 kg, by delivery are often piled up to 2 m high, Under extreme working condition, the use of the additional tool (knife) can lead to injury Operators often refuse to wear full protective clothing
4.	1st level	Cleaning work	Incorrectly done	Inhalation of toxic materials	2 min	

Based on the result of operator actions analysis tabulated in Table 6. 7, OAA-diagrams for normal operation can be developed to demonstrate the task sequence, possible errors and the necessary corrective actions. In this example, one step is considered as extremely important, since failures conducted during the performance of this step can cause significant impacts on both process and operator safety. This is the 3rd step of the task sequence, where one operator has to charge the solid materials in bags into the chamber by first lifting each bag from the palette onto the grid of the chamber, opening the bag using a knife, and pouring the content of each bag into the chamber through a sieve. Several failures are possible to happen during the performance of this task, due to the considerably high physical load. One batch will require around 25 to 40 bags of solid to be charged into the stir tank, each of which weighs between 12.5 to 25 kg. The working condition can be extremely hard for the operator, and under such extreme working condition, it is very likely that an operator refuses to wear full protective clothes or a full-face mask, since it will hinder his work pace. This is of course very dangerous, since without a full-face mask, fine solids can easily enter the respiratory system and can cause harm to health. During the completion of this step, it is also possible that due to a reduction in concentration the operator drops one or more bags that can cause dust formation and can eventually result in an explosion. Another danger can also happen under such high working load, that the use of a knife to open the bags leads to an injury.

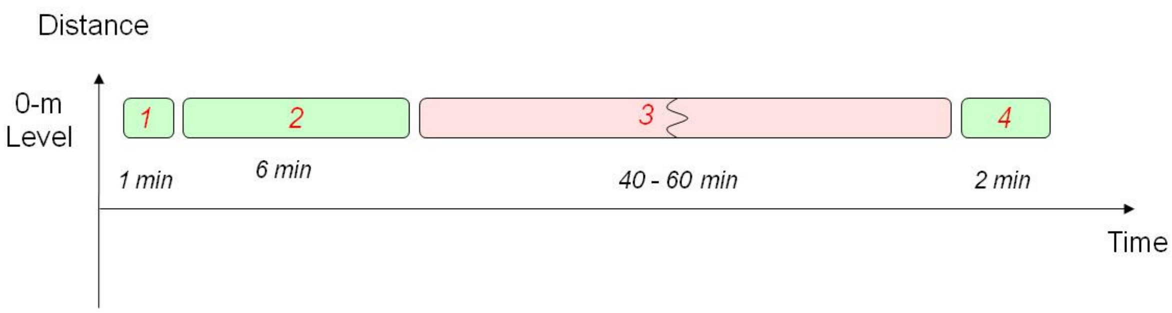

Figure 6. 6 Operator Actions Analysis (OAA)-Diagram for task 1.1.T2 in normal operation

After understanding several consequences that can be caused by errors conducted during the completion of task 1.1.T2, specifically during the 3rd step of the sequence, an evaluation of PIFs must be conducted to reveal the most influencing factors on operator performance, so that the most underlying problems and the necessary improvements to be made on the system can be recognized.

VI. The PIFs evaluation

The evaluation of PIFs is conducted to have a more comprehensive understanding of diverse factors that affect operators during the completion of certain tasks. For the task discussed in this case study, the evaluation of PIFs delivers a comparison of how strong the factors can influence the work of operators. By recognizing the most influencing factors, it will be possible to correspondingly understand the most necessary improvement to be conducted, to support the operators better during their work. Figure 6. 7 shows the result of PIFs evaluation for the task 1.1.T2. From the result, the most influencing factors in the performance of this task are physical load, additional tools, qualifications and experience, accessibility between plant sections, and plant layout.

The case study clearly demonstrates how the new HAZOPA systematically leads the way to find the most underlying problems that have been burdening the operators with unnecessary load. The factors recommended by HAZOPA to be improved are revealed through a systematic analysis of the interrelation between the plant's technical aspects and the human operators. By means of this new method, the legal requirement to conduct both safety and HF analysis can be fulfilled simultaneously, since the integration of plant personnel into safety concept is guaranteed.

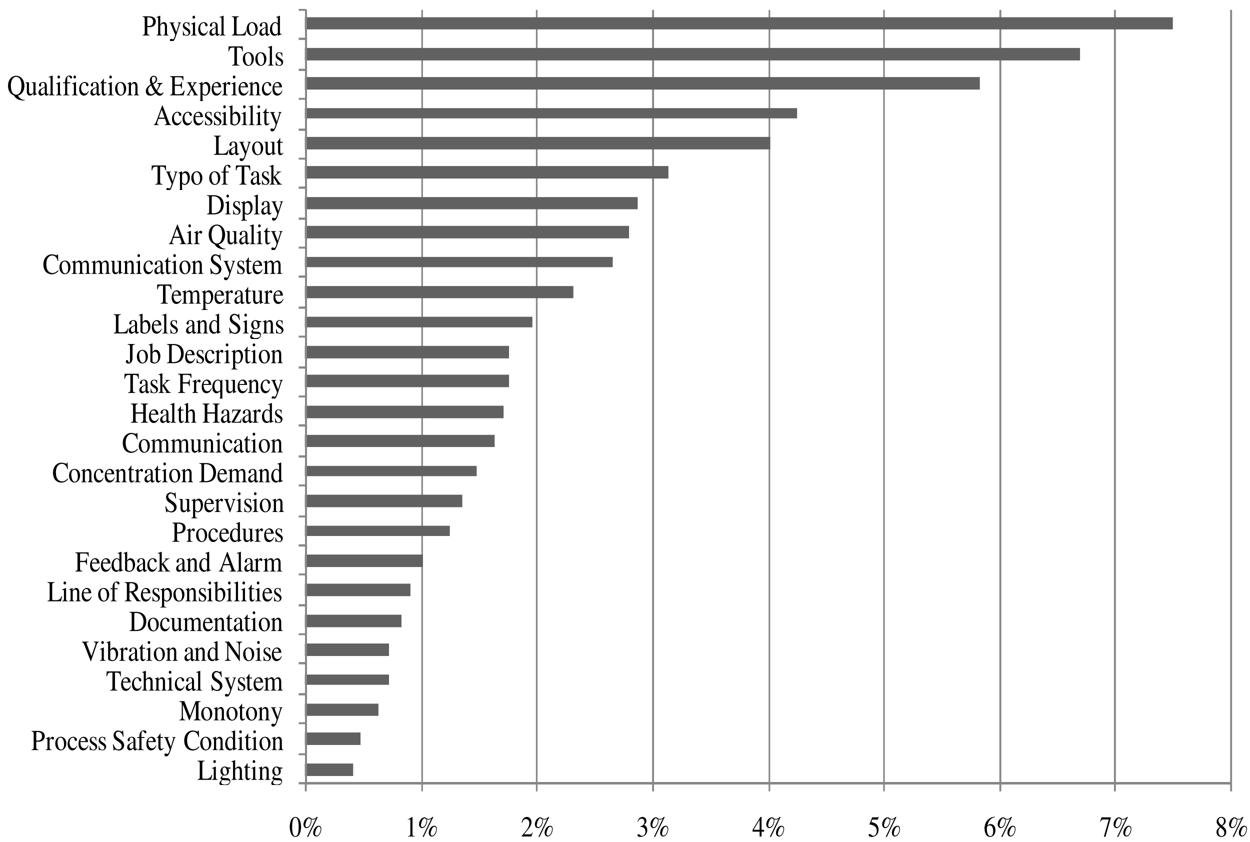

Figure 6. 7 Result of PIFs evaluation for task 1.1.T2

CHAPTER 7

APPROACH TO INCORPORATING HF CONSIDERATION INTO PLANT DESIGN

The previously developed computer-base method PITOPA (Chapter 5), although was proven capable in finding most necessary improvement potentials within a system to improve operation safety, is unfortunately less applicable for an implementation during design phase, where many information required to perform the means is not attainable yet. Nonetheless, considerations on HF are inevitable to be taken into account during design, since this is the exact time where actual attempts to avoid human error must take place. An enhancement of PITOPA is therefore required and conducted in this work, with the intention to develop a new approach that comprises both design and operation of a process plant.

7.1 Development of an Approach for HF Analysis in Design – *The PITOPA-Design*

A typical process design can be basically differentiated into three main phases; the conceptual, basic and detail engineering design phase. Subsequently, a commissioning stage will take place before the plant is taken into operation (Löwe et al., 2004). It is often very difficult to define the change-over between two different phases, and some activities conducted in a particular stage can lead to a need of modification on decisions taken in the previous stage. Figure 7. 1 shows the activities during the entire process design, where it can be seen that issues concerning human requirements are not directly focused upon.

Concurrent to the activities conducted during process design, HF consideration must also be taken into account. Unfortunately, the incorporation of HF into design phase is more complex than during process operation, since only little amount of information concerning the process is available at these early stages. Several methods attempt to implement HF during design, which unfortunately cannot comprise the whole design phase (McCafferty, 1995). This calls for a new approach that systematically assists the utilization of the limited amount of information during the whole design phase, to optimally minimize the potential problems related to HF issues later during operation.

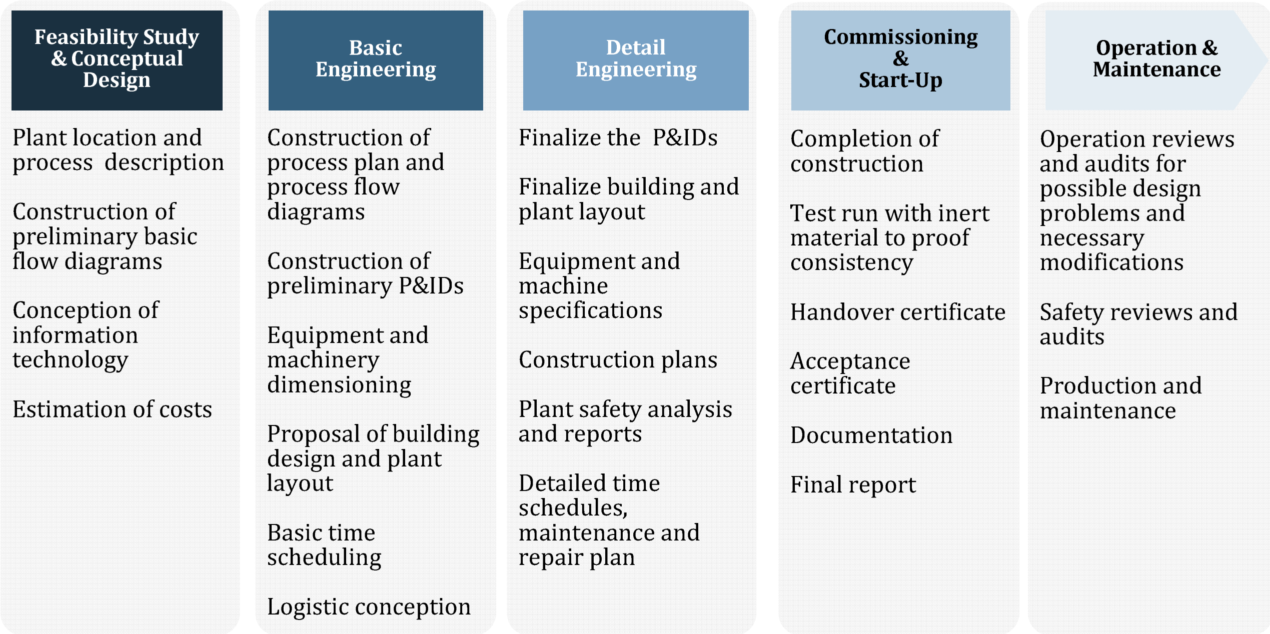

Figure 7. 1 Process design phases and the corresponding design activities of a process plant

The new method developed in this work, the *PITOPA-Design*, attempts to include different HF activities into each of the design stages shown in Figure 7.1. Some basic HF activities that are necessary to be conducted during those stages are (Widiputri, et al., 2009):

- Definition of all functions that require human contribution
- Identification and analysis of any kind of operator contribution and responsibility
- Designing all aspects relevant to HF to provide adequate support for operators
- Iterative HF design evaluation by taking into account operators' opinion
- Frequent performance of HF reviews and audits during operation to maintain plant's HF quality

The above activities are comprised in the 2 major components of PITOPA-Design, which are the *HFAD (HF Analysis in Design Phase)* and the *evaluation of HF design parameters*. The incorporation of these activities into the general engineering design is shown in Figure 7. 2.

Figure 7. 2 illustrates that HF activities by means of PITOPA-Design must be performed in relation to the ongoing engineering design. Some results gained from this HF analysis can call for modifications not only on the system's technical design, but also on the organisational structure of the work as well as the management system. Decisions made

during a particular stage can require changes on the design of certain aspects conducted in previous stages. Therefore, HF analysis during design must take place continuously and must assure that the interconnection between different stages of design process is maintained accessible.

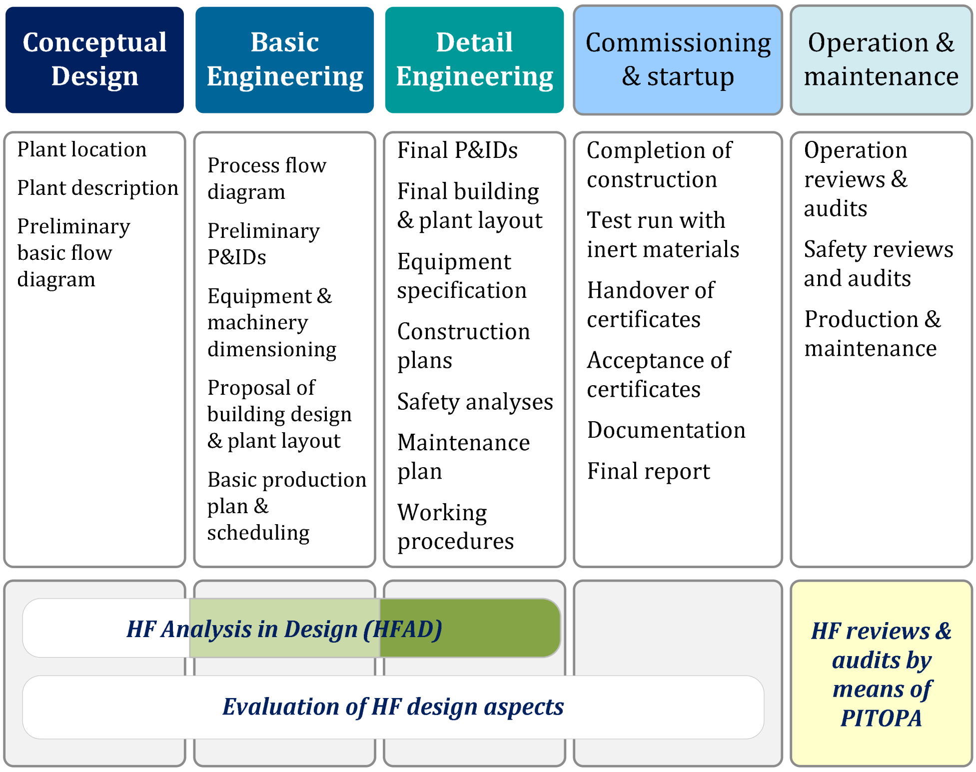

Figure 7. 2 HF design activities concurrent to engineering design by means of PITOPA-Design

The first component of PITOPA-Design, the *HFAD (HF Analysis in Design)* technique is developed to cover HF analyses in all 3 design stages. HFAD combines the implementation of different HF methods for design purpose, i.e. functional analysis, allocation of functions and task analyses, completed with the generation of *HF-Design (HFD)-catalogues* for every stage. The HFD-catalogues summarize results delivered by HFAD, pointing out the most necessary design considerations related to every HF-relevant aspect. The generation of HFD-catalogues employs questionnaires, which are developed in form of a systematic tree-structure to address the identification of potential HF issues and correspondingly suggest the necessary requirements on HF design parameters, in order to maintain process and personnel safety (Cramar, 2009). The suggestions provided by the catalogues, although not exhaustive, address the basic operators' requirements to be met by plant design. This way, the design team will receive more focused direction in finding most relevant design suggestions as recommended by the available practical guidelines and standards.

In order to comprise an implementation of HF analysis during the whole phase of a process plant design, HFAD is differentiated into three levels correspondingly, which are the *HFAD-Conceptual*, the *HFAD-Basic* and the *HFAD-Detail* with increasing particularities in every stage. If during conceptual design, considerations can only be made related to the plant's geographical conditions, in basic and detail engineering the analysis of human contribution can be performed in a deeper scrutiny. Figure 7. 3 illustrates the interrelation of all three design stages, in each of which the design of HF aspects becomes more and more specific.

Simultaneous with the performance of HFAD, the second component of PITOPA-Design, which is an iterative evaluation of HF design parameters must be conducted throughout the whole design and also during the commissioning. This evaluation has the aim to ensure that the engineering design meets HF requirements and also the other way around, that the design of various HF aspects still meets process's intentions and goals. Later on, a regular HF audits and reviews by means of PITOPA are necessary to maintain and improve the HF quality in the facility. A closer discussion about the HFAD and the technique for HF design evaluation is delivered in the following sections.

7.1.1 HF Analysis in Conceptual Design Phase (HFAD–Conceptual)

In early design phase or conceptual engineering, there is still a large opportunity and potential to optimally design the facility to meet production and safety requirements. This potential diminishes however with the increasing level of the design state, until at one point only minor changes can still be performed without causing significant cost implication. Hence, even with the least process information available in conceptual design, attempts to include HF consideration must already be made. In the early design phase or in conceptual engineering, considering HF can be facilitated through the performance of *HFAD-Conceptual*, where functional analysis and the allocation of functions take place as an initial step, as shown in Figure 7. 4. The aim of this analysis is to identify all functions that need to be fulfilled in achieving process's goals, and to recognize the necessary operators' involvement in each function.

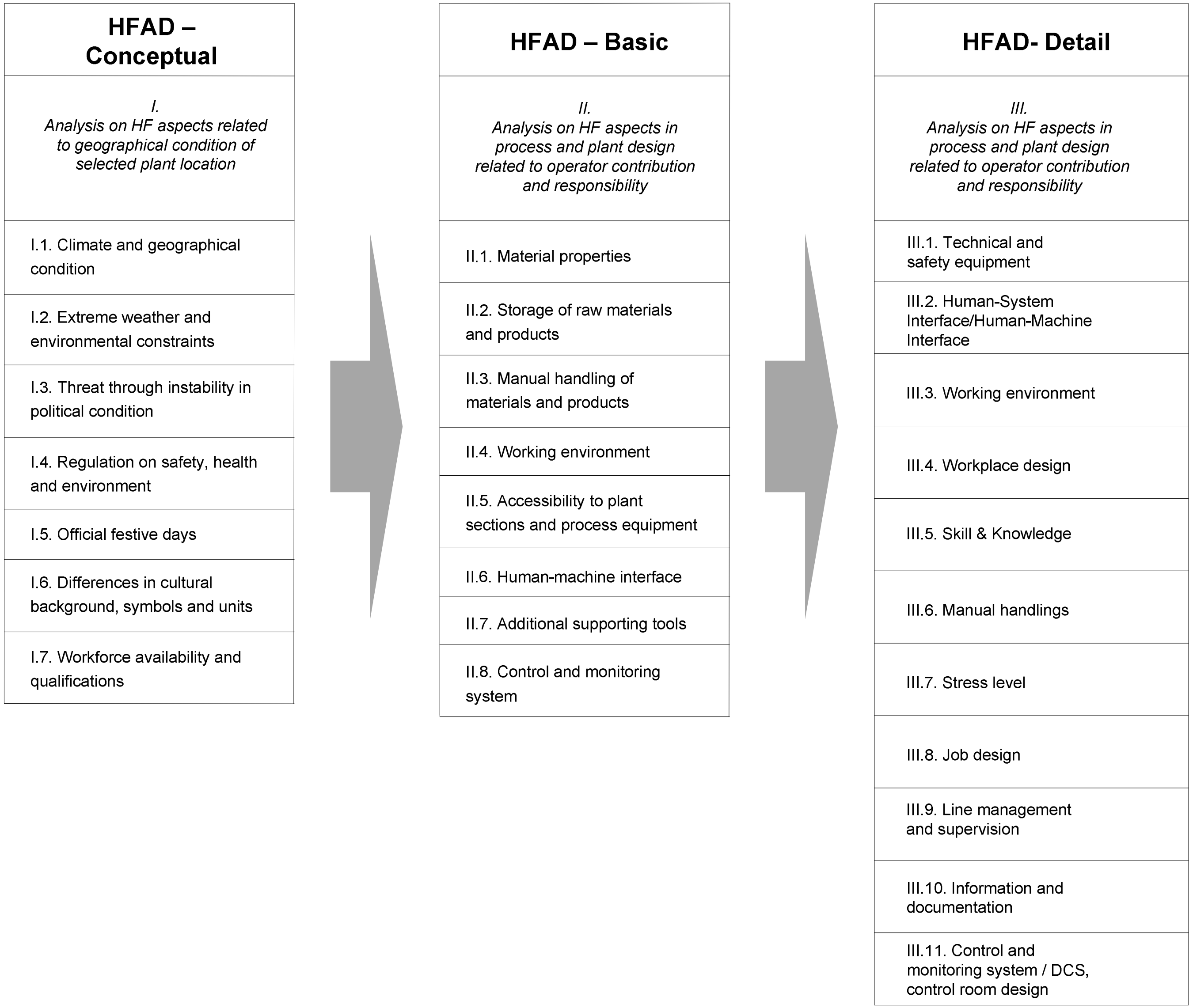

Figure 7. 3 Area of the HF analysis in each design stage

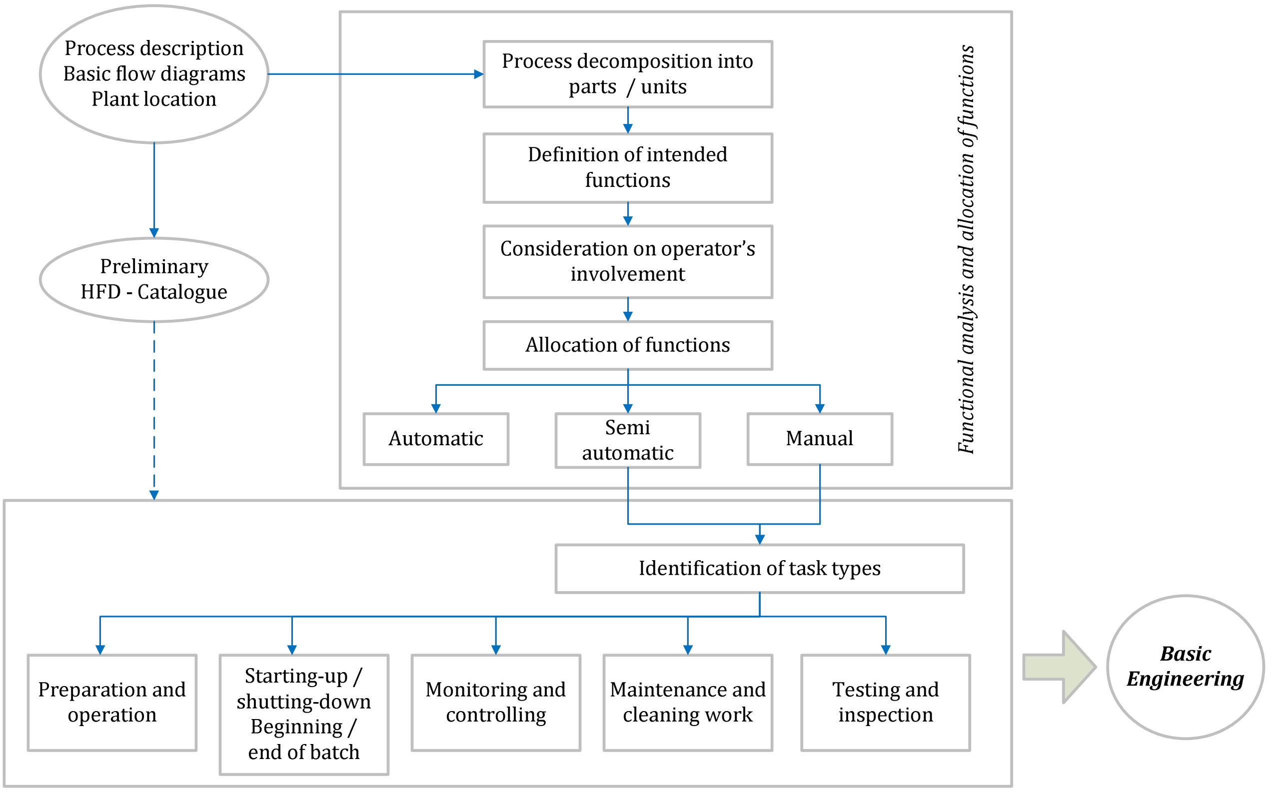

Figure 7. 4 HFAD in conceptual design (HFAD-Conceptual)

The consideration of HF can begin as early as the process has been defined. For the performance of functional analysis, the process is divided into smaller parts or units. Afterwards, the intended functions of every process part must be identified and analysed in term of the consideration about the required operator involvement to achieve intended purposes. Functions are afterwards allocated to machines only (automatic functions), to human operators only (manual functions) or to both machines and human (semi-automatic functions) (McCafferty, 1995). The functions which are decided to be operated semi-automatically and manually will be the focus of the next analysis.

Besides to identify functions and the requirement for operator's interference in achieving the purpose of those functions, early information about the process in terms of the selected plant location and in form of basic block diagrams can be utilised to recognize potential HF issues later during operation, so that necessary attempts to prevent them can be correspondingly taken. Considerations related to those potential HF issues will be summarized in the *Preliminary-HFD-Catalogue*, which will point out the most relevant and necessary design parameters in need of particular attention to avoid later problems. To generate this catalogue, an analysis by means of a tree-structured catalogue provided in Figure 7. 5 below must be conducted, which concerns these following aspects: i) climate and geographical conditions, ii) extreme climate and weather condition, iii) significant instability in political situations, iv) regional laws and regulations on safety and health, v) public holidays and festive days, vi) difference in cultural backgrounds and understanding on symbols and process units, and vii) manning availability and qualifications.

Table 7. 1 Five basic types of operator tasks

	Preparation and operation	***Process start-up / shut-down***	***Process monitoring and controlling***	***Maintenance and cleaning work***	***Testing, sampling and inspection***
Task description	• Handling of materials • Storage	• Starting-up the whole process, one part of a process, a process unit, or beginning a batch • Shutting-down the whole process, one part of a process, a process unit, or ending a batch	• Monitoring of operation at control room displays • Field monitoring • Decision making during deviations • Execution of solutions to problems • Documentation	• Maintenance activities both by own operators or third party workers • Cleaning of process equipment • General cleaning work	• Any sampling activity • Laboratory testing • On-site testing • Trouble shooting • Inspection of apparatus and equipment
Relevant design aspects	• Material properties • Storage • Working environment • Accessibility to process equipment • Additional tools • Safety equipment	• Console and control panels • Displays and human-computer interface • Working procedures	• Console and control panels • Displays and Human-computer interface • Design of DCS • Working environment • Control elements • Working procedures	• Material properties • Working environment • Additional tools • Safety equipment • Working procedures	• Material properties • Working environment • Accessibility to laboratories • Additional tools • Safety equipment • Working procedures

Still in the scope of HFAD-Conceptual, by making use of the results from functional analysis and functions allocation, as well as the suggestions delivered by the Preliminary-HFD-Catalogue, an analysis of all operator contribution must take place subsequently. This is a very critical step during design process, where information concerning all tasks, operators' actions and requirements are collected and analysed (Kirwan, et al., 2001). In early design stage, the first attempt to analyse tasks can be done through the classification of operator's contribution into 5 basic task types, as listed in Table 7. 1 above.

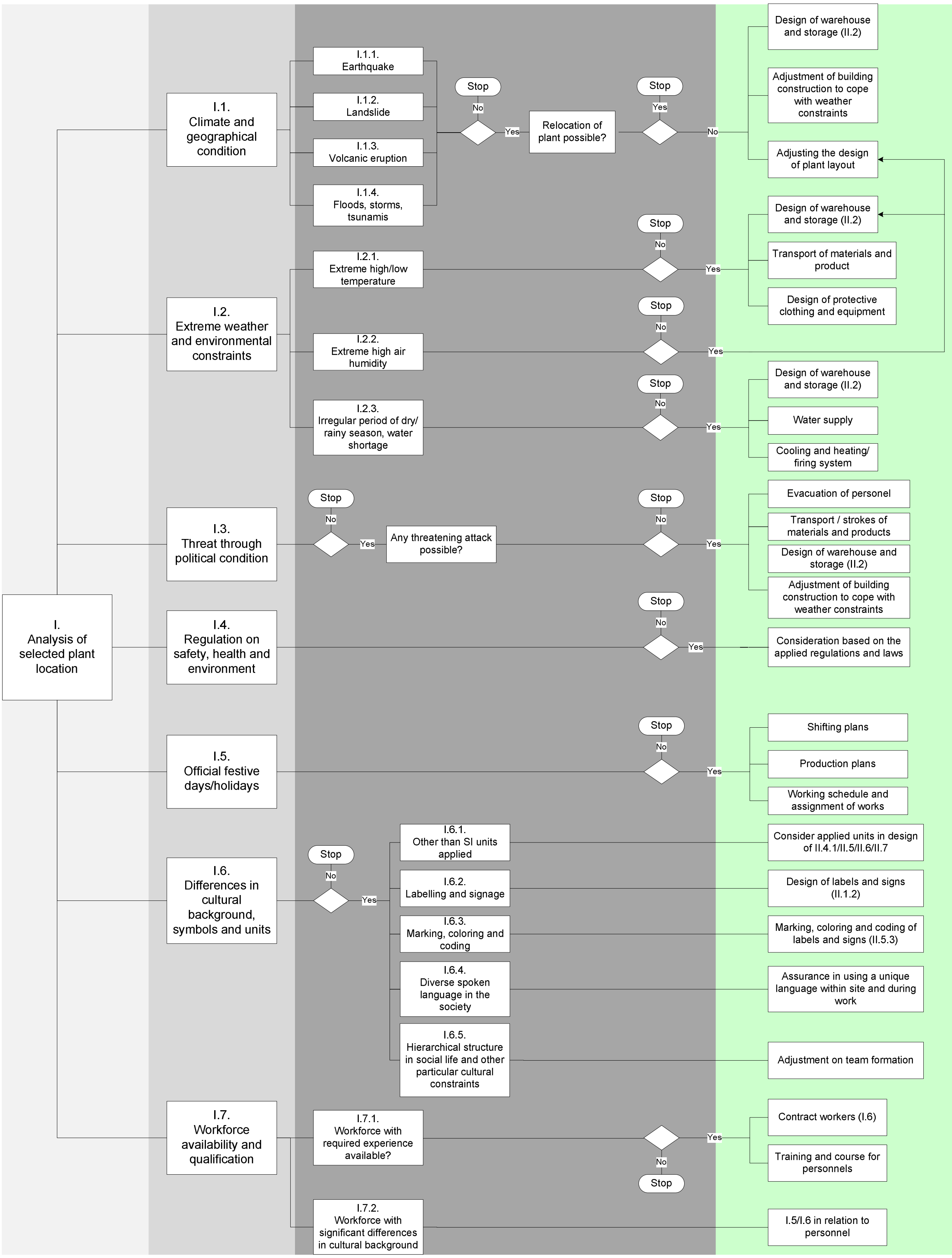

Figure 7. 5 Analysis of HF aspects relevant to geographical location of the plant

7.1.2 HF Analysis in Basic Engineering (HFAD – Basic)

After all functions in need of operator's contribution have been identified in conceptual engineering, and after the first identification of possible types of operator tasks, a more specific analysis on these tasks must be conducted in basic engineering. At this stage, HF has many opportunities to influence the design of both the process and the plant construction. As the design plan enters a more specific and concrete dimension, analysing HF can be done in a more real and exact way. Some necessary documentation in enabling the identification of operator tasks during basic engineering are i.e. the available process flow diagrams, preliminary P&IDs, conception of building design and plant layout, and also the Preliminary-HFD-Catalogue provided by HFAD-Conceptual. The analysis of HF in basic engineering is provided by the *HFAD-Basic,* whose implementation is presented in Figure 7. 6.

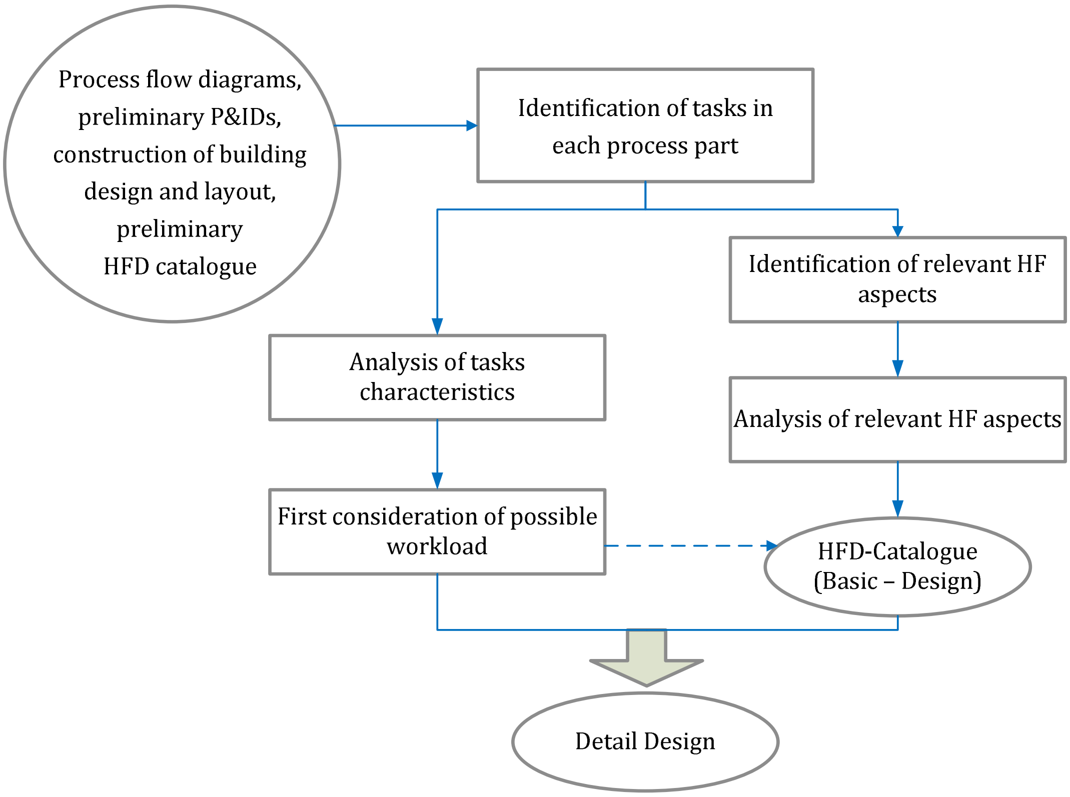

Figure 7. 6 HFAD in basic engineering (HFAD-Basic)

The HFAD-Basic is a combination between a task analysis and an analysis of relevant PIFs. For every identified function, the sequence of operator tasks is to be defined. In order to do so, experience from similar plants and expert opinions can be a very good source of information. After the identification of operator tasks, the characteristic of the tasks are to be analysed, and in addition to it, the relevant PIFs are to be identified. For this purpose, another set of tree-structured questionnaires was developed. The questionnaires comprise all HF aspects that must be considered before entering detail engineering, and will point out a list of the most necessary design parameters that hold the key to an inherently safe process and plant design.

HFAD-Basic provides a way to recognize unrealistic demands on operators, through an understanding about the possible inadequate working condition and dangerous characteristics of the tasks. The analysis will provide design considerations related to the following aspects, for each of which a questionnaire is available:

1. Material properties
2. Storage of raw materials and products
3. Manual handling of materials and products
4. Working environment
5. Accessibility to plant sections and process equipment
6. Human-machine interface
7. Additional supporting tools
8. Control and monitoring system

In analysing the characteristics of a task, some of the above factors are interrelated one with another. As an example, if one task deals with dangerous materials, then manual handlings of those materials, the required additional supporting tools and human-machine interface must be correspondingly designed. For this reason, in several cases, the completion of one questionnaire related to a certain aspect can refer to a further analysis of other aspects using other questionnaires. At the end of the analysis by means of HFAD-Basic, the *HFD-catalogue-Basic* will be provided, which summarizes all necessary HF design considerations to be incorporated during basic engineering and points out the most necessary HF design parameters for this purpose.

Following is a closer discussion about each of the aspects listed above together with the presentation of the associated tree-structured questionnaires for analysis purpose.

1. *Material properties*

   A crucial basic aspect to be analysed in terms of operator safety is the material properties involved in the whole processing. The properties of materials to be utilized, the intermediate and finished products affect the operators directly, especially in plants where manual handlings are to be conducted. Material properties of chemicals being treated in the process are among the most important concerns in determining the level of automation. The consideration comprises the followings:

- The hazard potentials of the utilized chemicals and products that may cause safety and environmental problems
- The hazards to workers through exposure with the chemicals

The above points are systematically structured in the questionnaire shown in Figure 7. 7. Several considerations provided from this analysis are focused to achieve an inherently safer design (ISD) through the four principles; minimisation, substitution, moderation and simplification. In addition to it, the catalogue will suggest the design team to take considerations concerning the necessary safety equipment, adequate job design, working procedure, labelling and signage corresponding to any possible hazardous property of materials.

2. *Storage of raw materials and products*

From the first sight it may seem that design of storage does not relate directly to HF and is more a responsibility of engineering design to handle. But, one cannot eliminate the fact that, there are operators who must spend almost all of their working time in warehouses. In other cases, some operators may have to travel a significant distance between warehouses and their actual work location, transporting dangerous materials with them. Related to the first aspect of the analysis in HFAD-Basic, which is material properties, the design of warehouse should meet several basic operators' requirements, such as:

- Proper ventilation to keep good air quality
- Systematic inventory system to avoid mix-up
- Location with a proper distance from any relevant part of process plant
- Availability of necessary tools in handling with materials in storage, in any form and size of packaging.

The questionnaire related with warehouse and storage of materials is shown in Figure 7. 8.

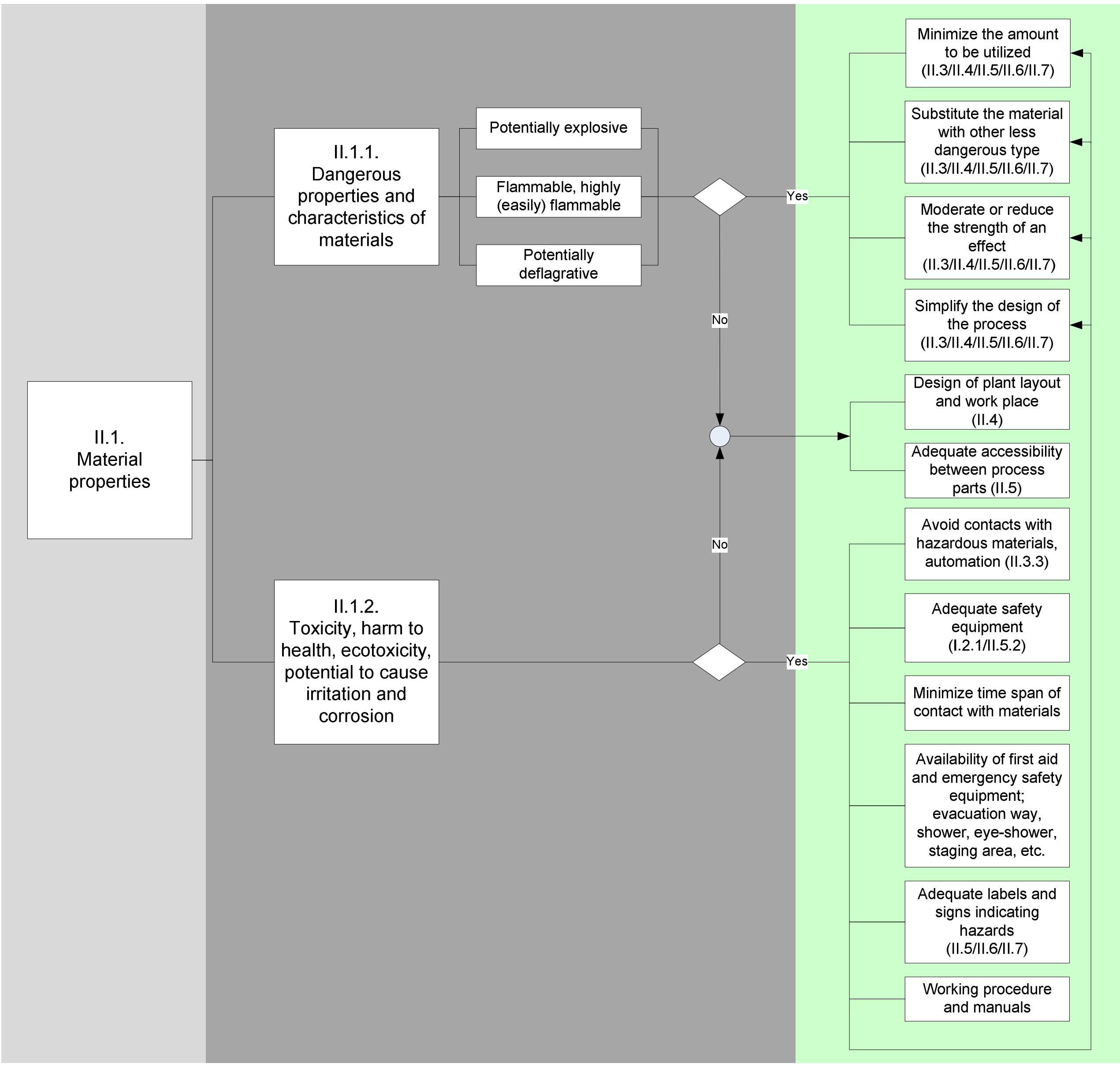

Figure 7. 7 HF design related to material properties

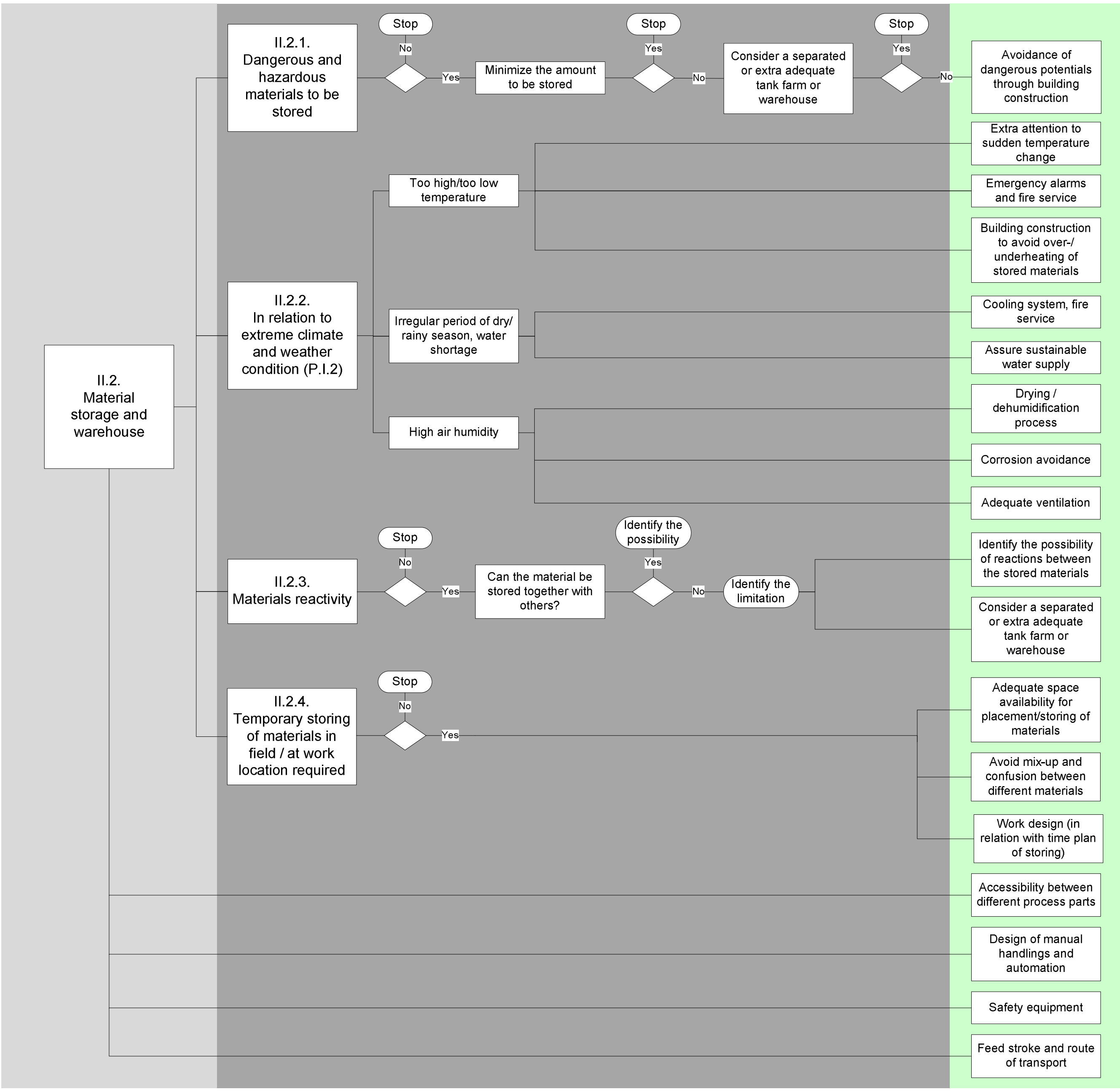

Figure 7. 8 HF design related to storage and warehouses

3. *Manual handling of materials and products*

After allocating the functions into automatic, manual and semi-automatic, HF consideration must be focused upon the manual parts of all functions, including those that are required for semi-automatic ones. The responsibility to conduct tasks manually will impact the operators directly both mentally and physically. Hence at this step, an analysis to re-check the allocation of functions is conducted. In the associated questionnaire (Figure 7. 9), some questions will ensure whether or not the related task should necessarily include operator's contribution. Although the allocation of functions was conducted previously in conceptual design, as more specific information about the process is available, the involvement of human operators in certain tasks must be further evaluated.

4. *Working environment*

   Operator performance is very easily influenced by the condition of working environment surrounding them. Besides the reduction in working performance, extreme working conditions can also cause permanent health problems. Several aspects related to working environment that must be taken into account during design are temperature, noise, vibration, and time of task completion; either at day or night time (Figure 7. 10). Again, a consideration to automate certain functions or tasks will be made at this point, since the recognition of possibility that an operator has to work under an extreme condition must address the need of automation.

5. *Accessibility to plant sections and process equipment*

   As the design proceeds with the development of preliminary plant lay-out, an analysis of accessibility in and between plant sections must be thoroughly conducted. Problems with insufficient access are often realized far too late during operation, where it will not be possible anymore to make any changes on the plant without causing excessive additional costs. The aspect 'accessibility' in this term is related with the required operator's effort to reach certain plant section or process equipment in completing the sequence of their job. The questionnaire for an analysis of this HF aspect is provided in Figure 7. 11, which includes the followings:

   - Distance between plant sections or process equipment that must be reached or operated by operators during the completion of tasks.
   - Availability of adequate path ways between plant sections and process equipment, including the clarity of path allocation to avoid confusion.
   - Exclusion of any possible awkward positioning while operators conducting their job.
   - Elimination of any contact with process equipment, chemicals or also additional tool that might cause harm to the operators.

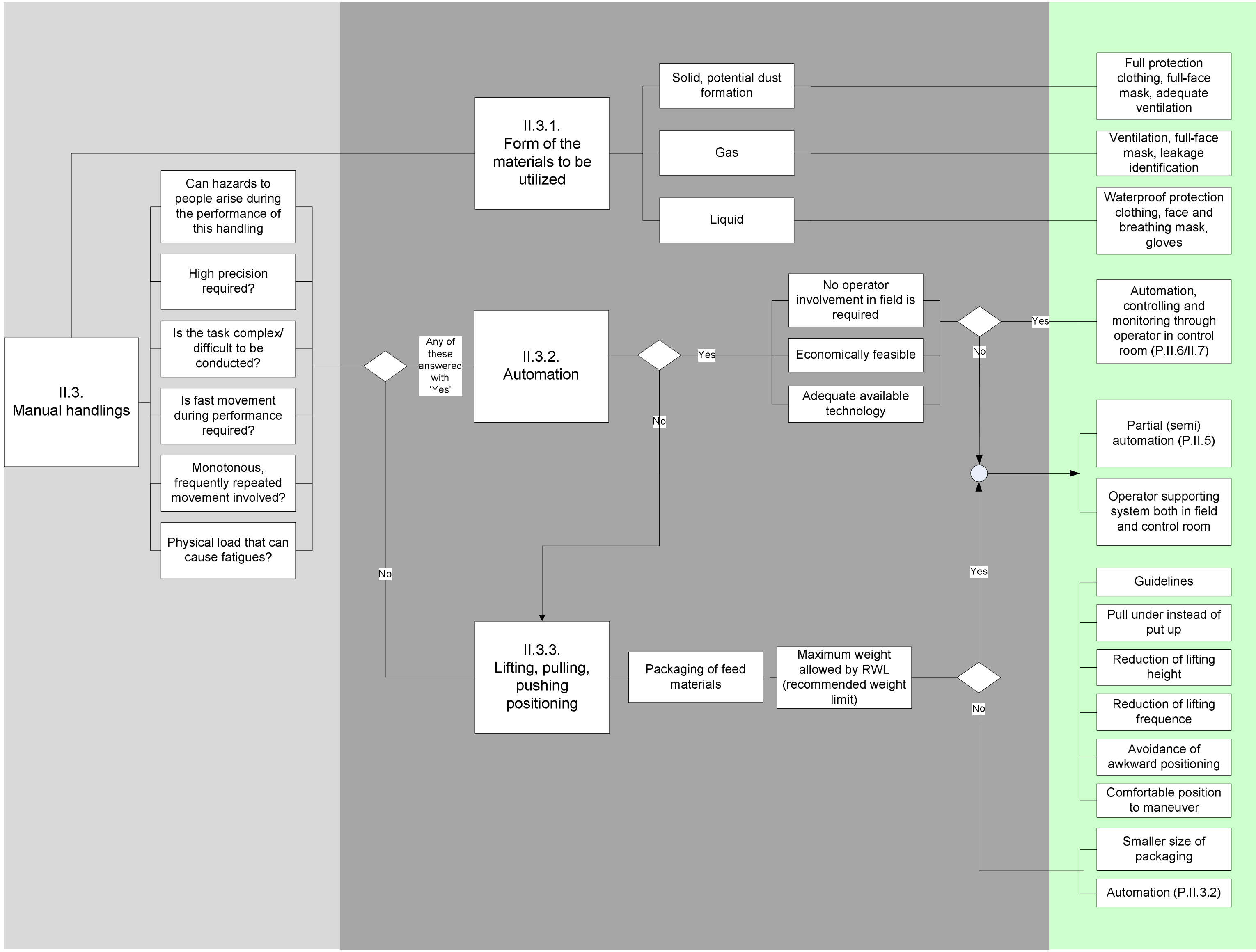

Figure 7. 9 HF design related to manual handlings

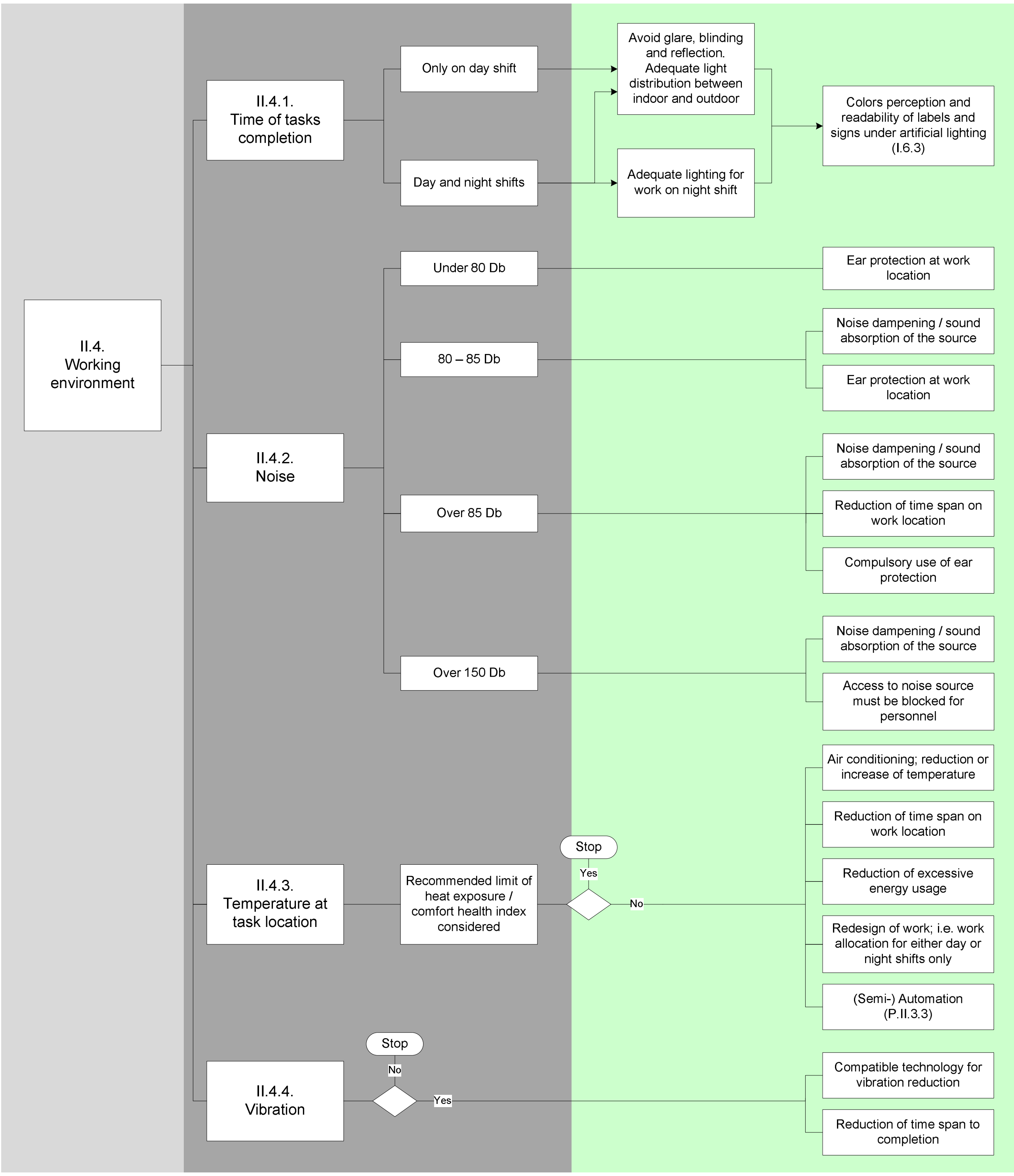

Figure 7. 10 HF design related to working environment

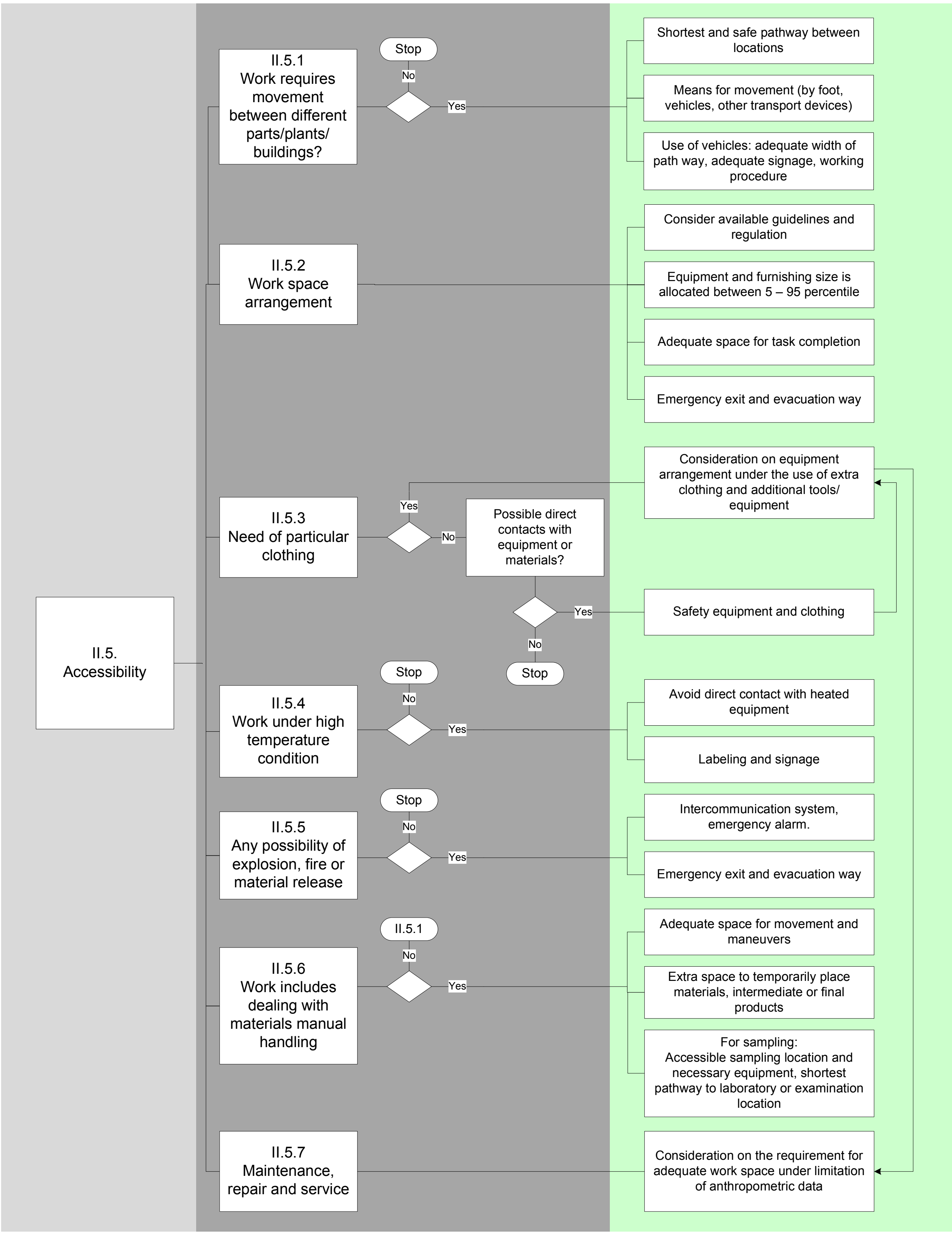

Figure 7. 11 HF design related to accessibility

6. *Human-machine interface and consoles*

   Consideration about human-machine interface (HMI) and design of consoles is normally made during detail engineering, which is actually already too late since at that stage, there is only minimal space left for the design team to make significant changes. On the other side, HMI is one of the main focuses of HF which will impact operators work directly, and is the only way for operators to communicate with the process. Therefore, HF consideration to analyse the design of HMI must be initialized as early as in basic engineering, although not every design parameter can be considered yet.

   The HF consideration concerning HMI in basic engineering will assist the recognition of possible interactions between operators and the system, in terms of to which extent operators' contribution is required in ensuring the operation to run expectedly. Points of analysis by means of the questionnaire in Figure 7. 12 are:

   - Recognizing the possibility of hazards and dangers arising during start-up and operation, and whether operators need to be present in field during these activities.
   - Ensuring the availability of necessary data and process logs for the operators. This will later relate with the adequacy of control and alarm log system, as well as working procedures.
   - Recognizing the possibility of any awkward positioning during work. In later design stages, the space for improving building and plant layout is extremely reduced.

   Many of design specifications of HMI i.e. displays configuration or data input devices can only be made based on market offers and availability. Standards and guidelines are available that suggest the appropriate HMI design based on best practices, and these guidelines can assist the design team in comparing technical specification and quality offered by different vendors. This activity will be optimal when conducted in detail engineering, as most of the required design specifications are already determined. Moreover, if the analysis of this aspect addresses the need to optimally adjust the design of control system (DCS) to operators' limitation, the catalogue will refer to a separate analysis of HF in DCS design, without giving more specific considerations concerning this subject.

7. *Additional working tools and operating elements*

   Availability of additional working tools must also be considered in early design stage. Additional tools can affect both the design of operator work as well as the process itself. If the use of a certain additional tool was related to the absent of one or more process equipment, either due to financial reasons, space availability or other reasoning, then the impact of using this tool on operator performance cannot be ignored. Often, additional tools that are intended to reduce operator load are in fact the source of problems during task completion. Such implication must be avoided through a better process and job design.

   Besides additional tools, the design of all operating elements must also take place at this point. Although it may seem small, design of operating elements must not be done later than in basic engineering, since in the next stage, in detail engineering, working procedures and manuals are to be arranged based on, among others, the design of operating elements. The associated questionnaire for this analysis is provided in Figure 7. 13.

8. *Control and monitoring system*

   Human-system interface might be a very important aspect that affects operator performance. However, since the actual aim of the design is to provide a good communication between the operators and the process, which means to enable a reliable process controlling and monitoring, the logic behind this interface becomes a very crucial aspect. In HFAD-Basic, the analysis on control and monitoring system design is done only at the superficial level. This includes the consideration of whether a field monitoring is required and the identification of the need to particularly perform decision-making during monitoring, which requires the operator to first notify and analyse the changing of process parameters. The questionnaire for this analysis is provided in Figure 7. 14.

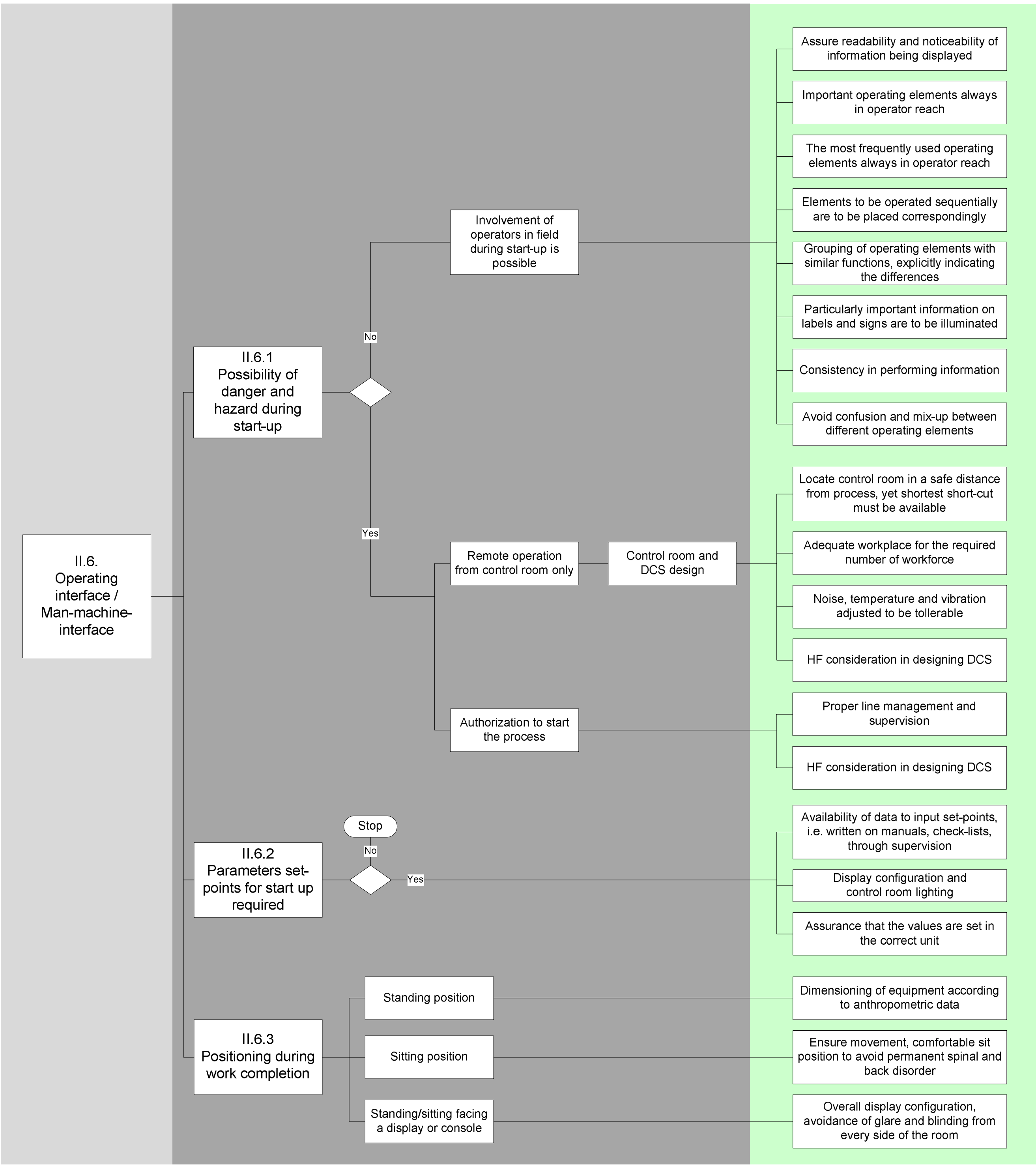

Figure 7. 12 HF design related to operating interface and human-machine interface

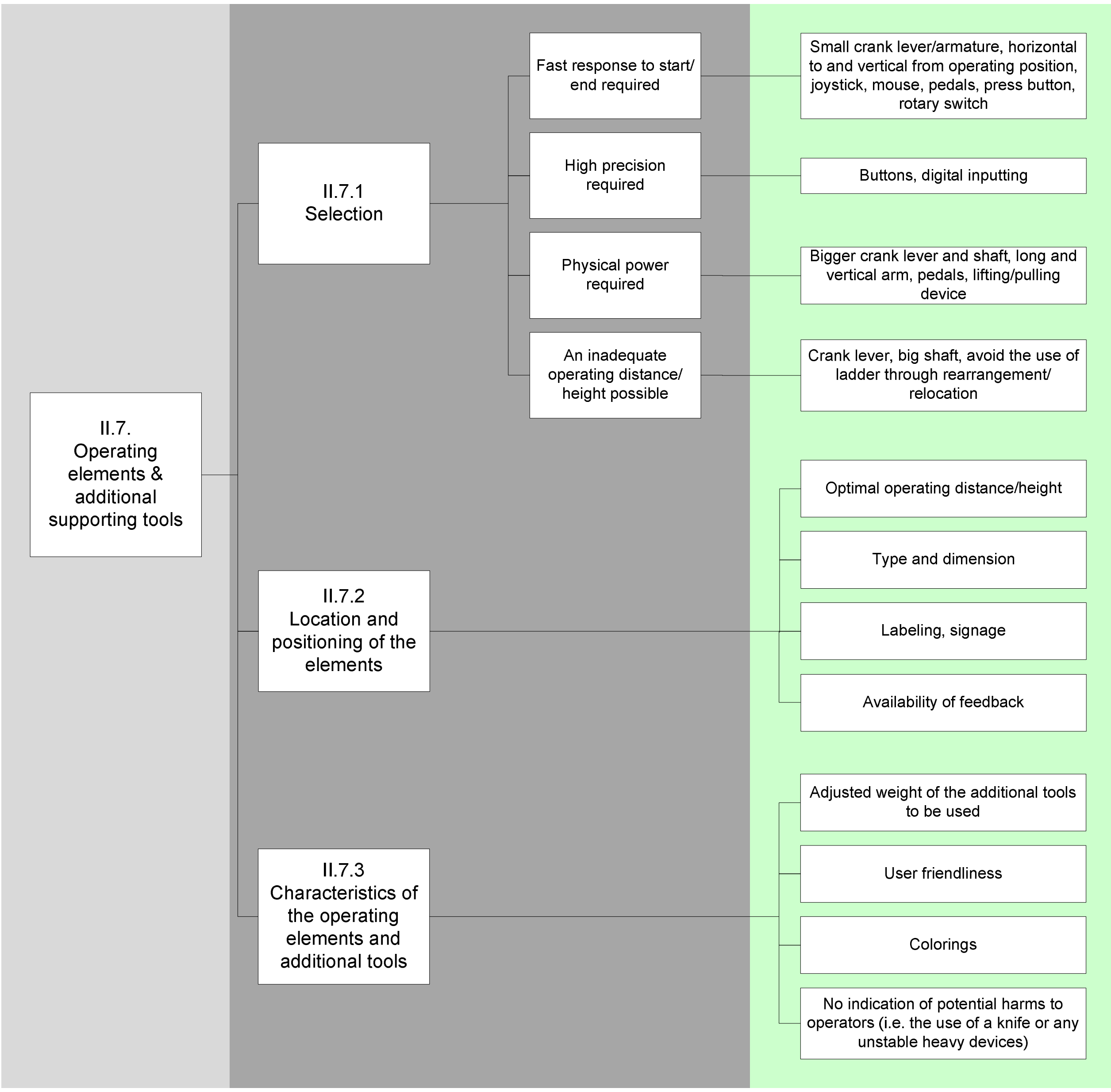

Figure 7. 13 HF design related to operating elements

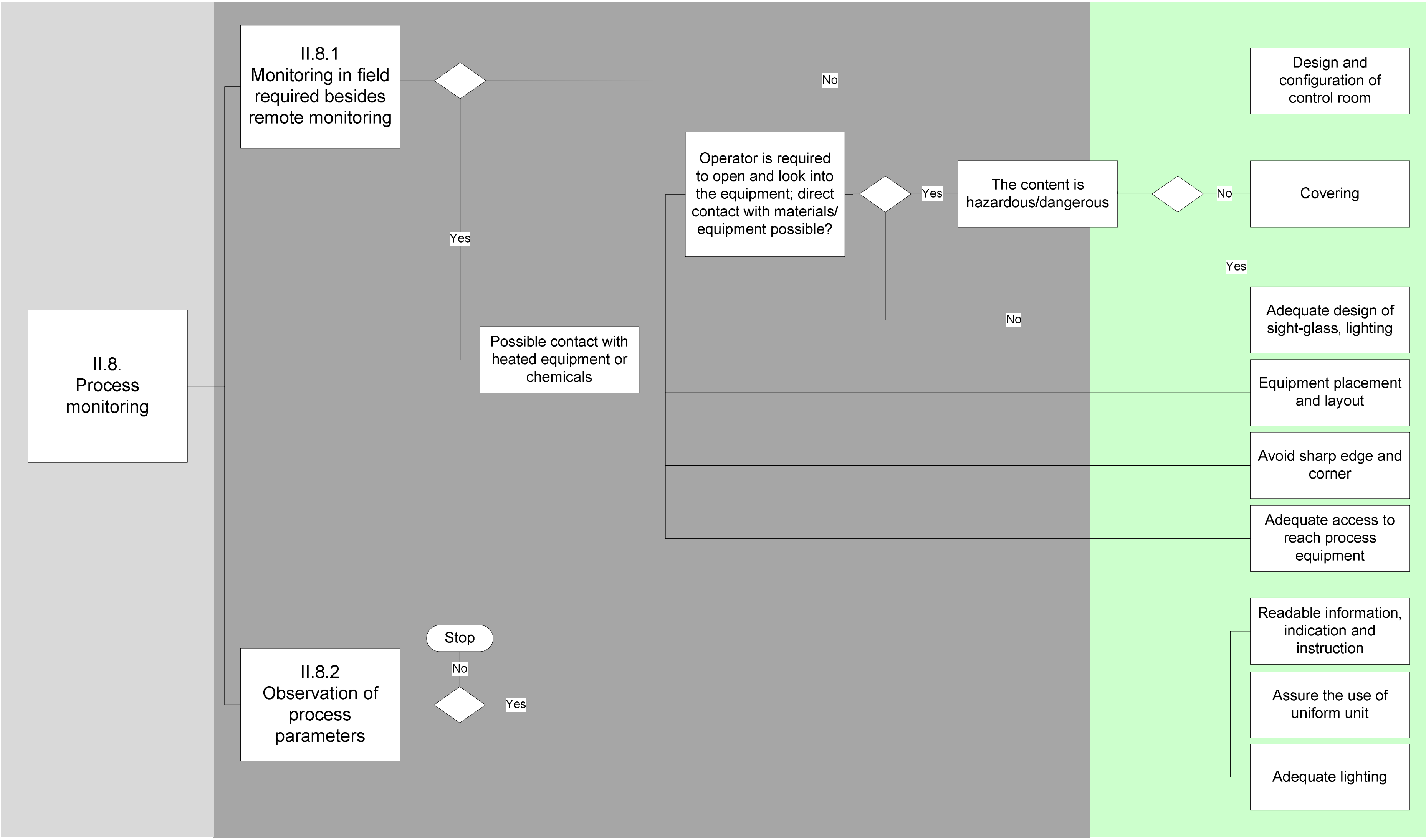

Figure 7. 14 HF design related to process monitoring

7.1.3 HF Analysis in Detail Engineering (HFAD-Detail)

Going further into detail engineering, the design team would already have been acknowledged with most of the requirements on engineering and technical design specifications that must be provided for the operation. The whole element of process design will be finalized by the end of this stage. Although the space for making changes and modifications on the ongoing design is considerably smaller than in previous stages, there are still potentials that must be thoroughly examined to optimize the system design, so that a higher efficiency and safer operation can be achieved.

For an analysis of HF in detail engineering, steps of the classic PITOPA (Chapter 5) need to be only slightly modified, since, as the design moves closer to reaching the final aimed configuration, the analysis of HF becomes more similar to an analysis of an existing facility. In terms of operator safety, HF considerations at this point must cover the design of all identified performance influencing factors (PIFs) relevant with operators' work within the system. In order to be able to locate the points in need of extra awareness, one must understand how the various PIFs can contribute in affecting human beings during their work.

The HFAD-Detail continues the analysis of tasks and HF aspects started in the previous stage. In basic engineering, task analysis has provided the identification of all tasks to be conducted by operators, together with the particular characteristics of the tasks as well as the possible load caused during performance of the work. HFAD-Basic also provides the design team with an HFD-catalogue-Basic, which suggest necessary HF design considerations for ensuring the system's HF quality. In detail engineering, the design of these aspects will be finalized, and therefore, further analysis of the identified tasks will be made. The analysis will identify the possible errors during performance, the cause or source of these errors, as well as the consequences brought by the error execution, which can either lead to an exposure to operators, causing an environmental damage, or process deviations in other parts of the process. A deeper understanding about how human operators interrelate with the process is therefore required. For this reason, the HFAD-Detail will implement the new HAZOPA (see the development in Chapter 6) to provide a wider scope of HF and safety analysis by combining their implementation during design of a process plant. The structure of HFAD-Detail is illustrated in Figure 7. 15.

As explained in chapter 6, the implementation of HAZOPA takes place using the available worksheet (Figure 6. 4) to identify the points where operator errors will have impact on process state, to identify necessary operators' contribution or interference following a process disturbance. As a result, operator actions analysis (OAA)-diagrams are provided. Through such an analysis, a comprehensive understanding on the interaction between operators and the system will be achievable. Moreover, the susceptible points where human errors can lead to a serious problem will be recognized. This information is crucial in correspondingly designing every HF aspect in the system, in order to provide adequate support for the operators, to improve their performance and to consequently heighten operation safety.

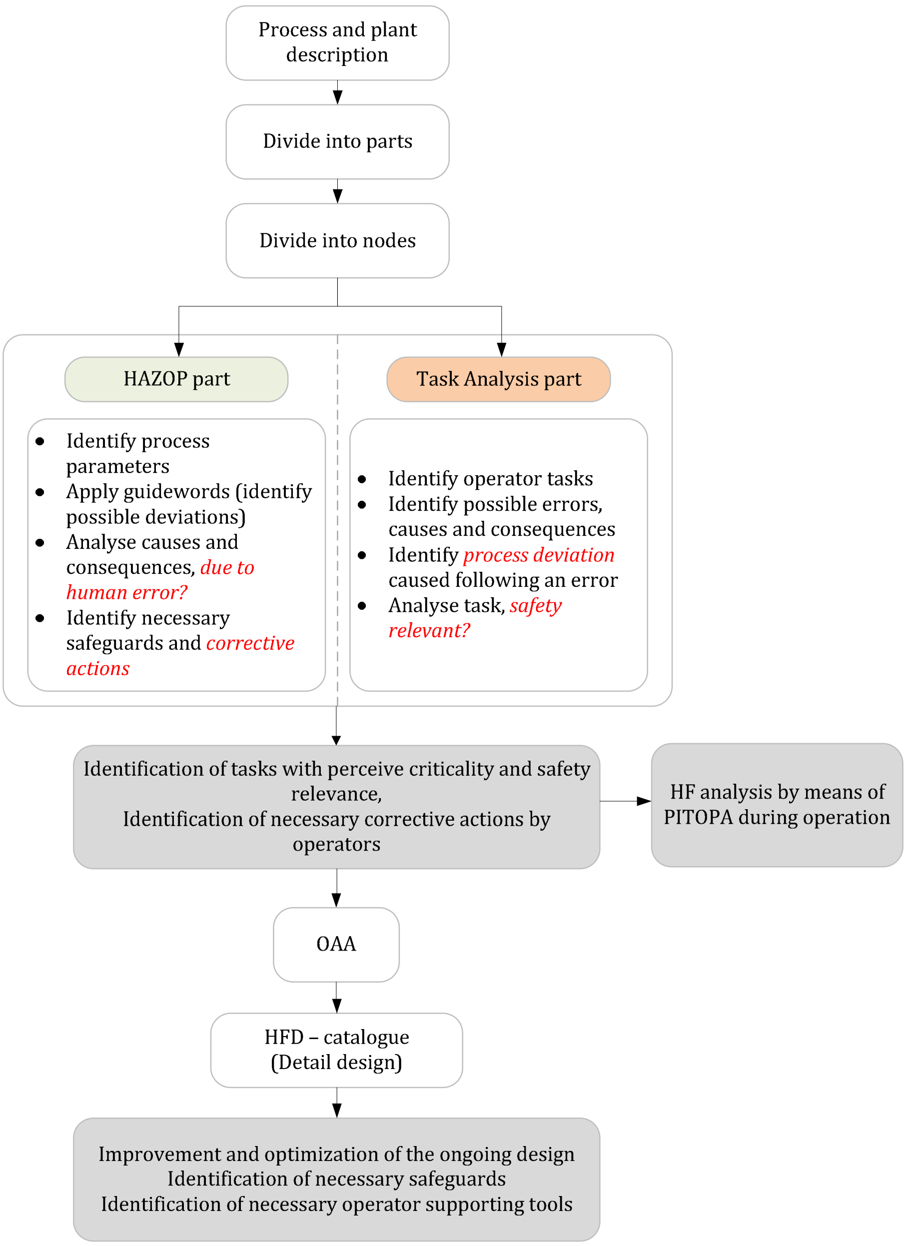

Figure 7. 15 Structure of HFAD in detail engineering (HFAD-Detail)

Subsequent to the implementation of HAZOPA, another HFD-catalogue will be generated for detail engineering. The development of this catalogue will cover more detail aspects than in both previous stages. A PIFs evaluation similar to which conducted during PITOPA needs to be performed for this purpose; however, the questionnaire used for the evaluation has been modified to suit an evaluation in detail engineering. The complete version of the questionnaire that assists the generation of *HFD-catalogue-Detail* is shown in *Appendix A*.

For the PIFs evaluation, similar to PITOPA, the factors are broken down into smaller attributes to provide a more detailed analysis, and each is assigned with relative weight (Table 5. 1). The result of this analysis will point out the HF aspects in need of design modification before coming into construction stage, or will address necessary information concerning each aspect to be taken into account during construction. At last, in addition to the suggestions for design optimization, the HFD-catalogue-Detail will also summarize the result of HAZOPA concerning the critical tasks and necessary corrective actions by operators following possible process deviations. This invaluable information must be maintained available for start-up and operation, and will serve as the basis for frequent HF analyses and audits during operation, in order to maintain or even to improve the system's HF quality from time to time.

7.2 Technique for HF-Design Parameters Evaluation

In making sure that the developed design meets the intended purpose, an evaluation must be carried out in each design stage, which will ensure that the ongoing design has taken into account the suggestions proposed by HFD-catalogues in the corresponding stage. Evaluation in every design stage must be done iteratively until the design team is convinced that the aspects to be designed in the corresponding stage have properly and adequately met operators' requirements in their work. Only afterwards, the design process can proceed to the next design stage. On the other hand, unsatisfactory evaluation results can require some modifications to be conducted related to decisions taken previously.

To facilitate the design evaluation of various aspects in each design stage, a new technique is developed. This new technique provides a way to cross-check the inclusion of all suggested considerations offered by HFD-catalogues, and therefore is principally a reverse of the analysis itself. Through the analysis by means of HFADs, the design team was made aware of various HF issues that might arise during operation, and has been given insights about how to correspondingly design different aspects in term of those HF issues. In the evaluation, the design team has to re-check whether the suggested design considerations have been undertaken (Voβ, 2009).

For the evaluation purpose, an evaluation form for conceptual design stage is available in Figure 7. 16, for basic engineering in Figure 7. 17, whereas the evaluation of HF aspects in detail engineering is made integrally during the generation of HFD-catalogue-Detail by means of the questionnaire in *Appendix A*. In making use of the evaluation forms, scores are used to represent the status of a HF design consideration (various design parameters relevant with HF) in their relation with the design requirement/objectives provided in HFD-catalogues. The scores that must be used to evaluate the level of enforcement of the suggested HF design considerations are listed in Table 7. 2 below.

Table 7. 2 Scores for HF design evaluation

Score	***Description***
0	Not relevant for specified location / specified task
1	Taken as design consideration & completed
2	Taken as design consideration, no completion yet
3	Not taken as design consideration yet

As an example, in conceptual design, the *Preliminary HFD-catalogue* suggests that the labels and signs (*HF design consideration no. S14 in Figure 7. 16*) must be designed in such a way that will cope with several aspects: differences in cultural backgrounds among workforce (*design requirements no. 17 to 21*) and in certain cases also the difference in qualifications background (*design requirements no. 22 and 23*). During the evaluation, the design team is required to check upon the settlement of the design consideration in fulfilling the required characteristics. Even though the final design of labels and signs can first be made later in basic or even in detail engineering, it is at this point important to be aware of the basic constraints in designing those labels and signs related to the varying cultural backgrounds among the personnel.

No.	HF Design Consideration	Design Objectives	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Mean SCORE	Remarks
	Evaluation Form		*Climate & geographical condition*					*Extreme weather constraints*			*Instable political situation*		*Regulation on safety, health & environment*			*Official holidays & festive days*			*Difference in cultural background, symbols & units*					*Workforce Avail. & qualifct.*			
	HFAD in CONCEPTUAL Design	No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23		
	Analysis of HF aspects design related to geographical condition of selected plant location	Design Objectives	Use of guidelines (e.g. whole building design guidelines and regulation)	Earthquake proof design	Landslide proof design	Resistance to exposure through volcanic activities	Storm, tsunamis and flood resistance	To handle extreme high/low temperatures	To handle high air humidity	To solve problems with water supply (irregular periods of dry season)	Consider damages through attacks or vandalism	… *(add, depends on the specific case)*	EU standards	Guidelines of the German Hazardous Incidents Commission	Guidelines for technical & engineering work in Hessen	Consider days where production is not allowed to run	Consider days where operators are not allowed to work	… *(add, depends on the specific case)*	The use of SI units as measurement unit	Different familiar symbols in labeling & signage among workforce	Different familiar colors, markings & codes among workforce	Diverse spoken languages among workforce/ society in general	Consider hierarchical structure in social life & other cultural constrains	Required experience	Required qualifications	Mean SCORE	*Remarks*
S1	Design of warehouse and storage		x	x	x	x	x	x	x	x	x		x	x	x												
S2	Adjustment of building construction (to cope with geographical condition)		x	x	x	x	x				x	x															
S3	Design of plant layout		x	x	x	x	x	x	x	x																	
S4	(1.2.1) Transport of materials and products							x	x	x	x	x															
S5	(1.2.1) Safety clothing and equipment							x	x	x																	
S6	(1.2.3) Water supply sufficiency							x	x	x																	
S7	(1.2.3) Temperature control system							x	x	x																	
S8	Emergency exit & evacuation way										x	x															
S9	Design consideration based on applied regulations and law												x	x	x												
S10	Shifting plans															x	x	x									
S11	Production plans															x	x	x									
S12	Work scheduling and assignment of works															x	x	x									
S13	Use of the same units on the whole design																		x	x	x	x	x				
S14	Design of labels and signs																		x	x	x	x	x				
S15	Marking, coloring and coding of labels, signs, information display																		x	x	x	x	x				
S16	Use of a unique language																		x	x	x	x	x				
S17	Team formation																		x	x	x	x	x				
S18	Consideration to outsource																							x	x		
S19	Training and courses																							x	x		

Figure 7. 16 Form for design evaluation in conceptual design

The HF design considerations listed on the evaluation form are to be assigned with a number between 0 and 3 to describe its status in the ongoing plant design, whether they have been taken into consideration and completed in meeting certain design objectives. However, there are spaces on the evaluation forms, which must be left blank (presented as the gray area on the evaluation forms), since several design considerations cannot be evaluated in term of certain HF aspects. Only the white boxes on the evaluation forms need to be filled-in with a score for the evaluation purpose.

The score 0 in this case represents an irrelevant requirements on the design of certain HF aspect. This may apply for instance in a specific case where the available workforce comes from a unique cultural background and a culture difference will not be an issue at the location where the plant is to be constructed, then for the HF design consideration no. S14 (in conceptual design stage), the design requirements no. 17 to 21 will not be relevant anymore and their relation with S14 must be assigned with the score 0.

The scores 1, 2 and 3 represent a decreasing level of inclusion and completion of the considerations; either they have been completely incorporated into design process, have been taken into consideration but not realized yet, or have not been taken into consideration at all, respectively. The items that are assigned with either score 2 or 3 are to be highlighted and marked with other colours (yellow to represent score 2 and red to represent score 3) to remind the design team that those items are still in need of further action. If no more attempts can be performed in the current design stage to change the status, yet it is still marked with yellow or red, then this HF design consideration must be taken into account in the next stage. The same rule applies for the evaluation of HF design in basic engineering. To better demonstrate the implementation, this new evaluation technique is applied to the case-study together with the implementation of PITOPA-Design as delivered in Chapter 8.

Evaluation Form

HFAD in BASIC Design

Analysis of HF aspects design related to operators' contribution and responsibility

Design Objectives

Group	No.	Design Objective
Material properties	1	Considering the use of flammable materials
	2	Considering the use of explosive/deflagrativ materials
	3	Considering the use of highly reactive materials
	4	Considering the use hazardous materials : toxic, corrosive, irritating
Material storage & warehouse	5	To handle extreme high/low temperatures
	6	To handle high air humidity
	7	To solve problems with water supply (irregular periods of dry season)
	8	Considering limitations for storing together with other materials
	9	Allowing temporary storing at work location
Manual handlings	10	Considering the form of materials to be handled manually (solid, gas or liquid)
	11	Avoiding hazards to people during handling
	12	Ensuring high precision
	13	Ensuring speed (fast movement)
	14	Supporting monotonous frequently repeated movement
	15	Supporting tasks with high physical load
	16	Supporting tasks requiring lifting, pulling, pushing positioning
	17	Considering suitable guidelines
Working environment	18	Support task completion on day shift
	19	Support task completion on day & night shift
	20	Protection from excessive noise
	21	Protection from heat exposure at location
	22	Protection from excessive vibration effect
Accessibility	23	Support tasks requiring movement between buildings/plants/parts
	24	Providing adequate space for task completion & for temporary material storing
	25	Allowing movement and maneuver under the use of protective clothing & equipment
	26	Allowing movement between heated equipment
	27	Coping with possibility of fire, explosion or material release
	28	Adequate space for manual handlings
	29	Allow maintenance, repair and service
Operating interface/ Man-machine interface	30	Support field operators during startup
	31	Support control room operators during startup
	32	Ensure correct data inputs
	33	Work in standing position
	34	Work in sitting position
	35	Support work facing a display/console/ control panel
Operating elements & additional supporting tools	36	Allowing fast response
	37	Allowing high precision
	38	Ease tasks requiring physical power
	39	Support tasks dealing with inadequate reaching distance
	40	Reachable positioning of necessary equipment
	41	Operating element with adequate supporting characteristics
Process monitoring	42	Support field monitoring with possible direct contact with materials or equipment
	43	Support field monitoring with NO possible direct contact with materials or equipment
	44	Provide support for parameter monitoring and controlling

No.	HF Design Considerations	Related to tasks: No.	Task	Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	Mean SCORE	Remarks
S1	Design of warehouse and storage																																																	
S2	Adjustment of building construction (to cope with geographical condition)								x																																									
S3	Design of plant layout				x	x	x	x																																										
S4	(1.2.1) Transport of materials and products																																																	
S5	(1.2.1) Protective clothing and equipment							x																						x	x																			
S6	(1.2.3) Water supply sufficiency										x																																					
S7	(1.2.3) Temperature control system																																																	
S8	Emergency exit & evacuation way																												x		x																			
S9	Design consideration based on applied regulations and law																																																	
S10	Shifting plans																																																	
S11	Production plans																																																	
S12	Work scheduling and assignment of works												x												x																									
S13	Use of the same units on the whole design																																			x													x		
S14	Design of labels and signs																					x	x																					x				x		
S15	Marking, coloring and coding of labels, signs, information display																					x	x																					x						
S16	Use of a unique language																																																	
S17	Team formation																																																	
S18	Consideration to outsource																																																	
S19	Trainings and courses																																																	
S20	Amount reduction of dangerous materials				x	x	x	x																																										
S21	Substitution of dangerous materials				x	x	x	x																																										
S22	Effect moderation				x	x	x	x																																										
S23	Design simplification				x	x	x	x																																										
S24	Accessibility (point II.5); reachablility, pathway				x	x	x	x	x	x	x	x	x															x	x																			x			
S25	Avoidance of contact with hazardous materials							x																																										
S26	Contact time minimization							x																																										
S27	Degree of automation							x	x	x	x	x	x		x	x	x	x	x	x	x				x																									
S28	Emergency safety equipment: Eye-wash, shower, staging area, evacuation way, etc.							x	x	x	x	x	x																																					
S29	Feed stroke & route of transport								x	x	x	x	x																																					
S30	Monitoring of temperature change								x																																									
S31	Emergency alarms & fire services								x		x																																							
S32	Cooling system										x																																							
S33	Drying/dehumidification process									x																																								
S34	Corrosion avoidance									x																																								
S35	Identification of possible reactions between materials						x					x																																						
S36	Warehouse location				x	x	x	x				x																																						
S37	Full protection clothing, full face mask													x																																		
S38	Waterproof protection clothing													x																																		
S39	Ventilation									x				x																																		
S40	Leakage identification system													x																																		
S41	Operator supporting system in field														x	x	x	x	x	x	x																											
S42	Operator supporting system in control room														x																																	
S43	Consideration on design parameters based on guidelines for ergonomics															x	x	x	x	x	x																											
S44	Pull under position instead of put up																		x	x	x																											
S45	Lifting height																		x	x	x																											
S46	Lifting frequence																		x	x	x																											
S47	Avoidance of awkward positioning																		x	x	x																											
S48	Comfortable positioning to maneuver																		x	x	x																											
S49	Packaging dimensioning																		x	x	x																											
S50	Avoidance of glare, blinding and reflection																					x	x																	x										
S51	Adequate lighting																					x	x																							x		x		
S52	Use of ear protection																							x																										
S53	Noise dampening, sound absorption																							x																										
S54	Time span reduction at location																							x		x																								
S55	Blocking of access to source of noise																							x																										
S56	Air conditioning																								x																									
S57	Reduction of excessive energy usage																								x																									
S58	Re-allocation of work to other shifts																								x																									
S59	Vibration reduction																									x																								
S60	Dimensioning of equipment and furnitures																											x				x	x				x	x												
S61	Equipment arrangement, workspace adequacy											x																x				x	x														x				
S62	Means for movement; vehicles, transport device																										x											x												
S63	Access to intercommunication system																														x																			
S64	Sampling location and equipment																										x				x	x																		
S65	Information readability																					x	x												x														x		
S66	Placement of operating elements, reachability																																		x															
S67	Grouping of elements with similar functions																																		x															
S68	Illumination of labels and signs displaying extra important information																					x	x												x															
S69	Consistency of information display																																		x															
S70	Avoidance of confusion and mix-up											x																							x															
S71	Control room location																										x								x														
S72	Control room dimensioning																																			x														
S73	DCS Design																																			x														
S74	Data availability for inputting set-points																																			x	x													
S75	Display configuration																																			x				x										
S76	Control room lighting																																			x	x			x										
S77	Correct selection of operating elements																																		x	x	x				x	x	x	x		x				
S78	Dimensioning of operating elements																																		x	x		x	x							x				
S79	Positioning & placement of operating elements																																		x	x	x	x	x	x					x					
S80	Feed-back availability																																		x	x	x				x	x							x		
S81	Design & configuration of control room																																			x		x									x	x			
S82	Covering & containment of process equipment																																														x				
S83	Design of sight-glass																																														x				

Figure 7. 17 Form for design evaluation in basic engineering

7.3 Intermediate Summary

The performance of the new PITOPA-Design enables the utilization of available information in every ongoing design stage for HF analysis purposes by means of HFAD, the development of HF Design (HFD)-Catalogue and through design evaluation during each of the three design stages. Resulting from PITOPA-Design is an optimal design of process plants that meets both HF and technical/engineering requirements and a promotion of general process and operation safety in the new (or modified) plants. The implementation of PITOPA-Design is once again summarized in a simplified form in Figure 7. 18.

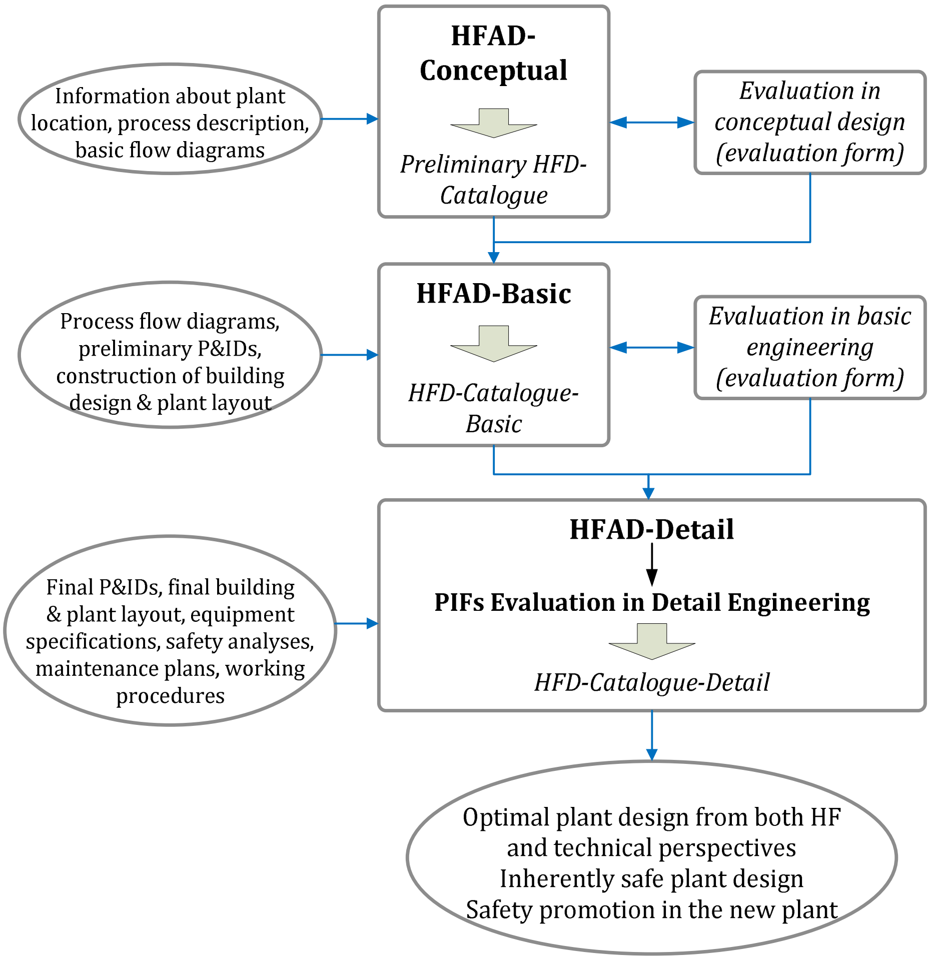

Figure 7. 18 Implementation of PITOPA-Design

CHAPTER 8

IMPLEMENTATION OF THE NEW PITOPA-DESIGN: A CASE-STUDY

In order to exemplify the implementation of the new HF approach during process design, the hypothetical case-study discussed previously in Chapter 6 (the development of HAZOPA), will be taken in further discussion. In the previous case-study, a simple mixing process was taken under analysis by means of HAZOPA, where the results addressed several system weaknesses that can directly or indirectly contribute to cause operator errors, leading to a disaster. In an existing facility, such system weaknesses must be eliminated through different process improvements, which mostly hindered by either space unavailability, difficulties to make changes due to the complexity of the plant, or most importantly by the lack of financial source for process changes. Those weaknesses nonetheless, could have been avoided if during process design the engineers had been acknowledged with issues concerning HF. Designing the process must have addressed human limitations, so that later, the system will meet operator needs and can endure their tendency to err.

In this chapter, the mixing process discussed earlier will be taken back into the design phase. Without much information about how the plant will later be operating and about what the exact responsibility the operators will have during operation and monitoring, HF considerations will be included into the design of this mixing process. This case-study will demonstrate the capability of the inclusion of HF considerations in design to avoid later changes and unplanned costs during operation.

8.1 Conceptual Design

At the beginning of the design, the design team is only provided with limited amount of information concerning the process and consequently, in HFAD-Conceptual only considerations related to plant location and its geographical conditions can be made, in a combination with the performance of functional analysis and the allocation of functions. Afterwards, the possible operators' involvement identified in each function will be classified into 5 different task types listed in Table 7. 1.

In this case-study, the selected location for the new process plant is the western part of Germany. The new plant will produce several types of chemicals, depending on production scheduling. The plant will be located in a new building, separated from other processes since product contamination is to be completely excluded. Several HF design considerations related to its geographical location are summarized in the "Preliminary HFD-catalogue" in Table 8. 1. The catalogue is an outcome of the questionnaire for conceptual design in Figure 7. 5, which was answered after the following discussions:

1. *Climate and geographical conditions.* Concerning climate and geographical condition of the selected plant location, which is Germany, no relevance should be taken into account in relation to potentials of earthquakes, landslide, volcanic activity or flooding.

2. *Extreme weather and environmental constraints*. There are 3 main conditions to be concerned of in relation to weather condition and environmental constraints, which are: tendency of extreme temperatures, high air humidity and irregular dry seasons that can cause water shortage. For Germany, the last condition is considered to be irrelevant, since water supply is always sustainable. Extreme temperature is generally not an issue, however, in the latest five years there has been a shift in temperature range that leads to some anomalies, and extreme low (below -20 ^oC) or high temperature (up to 38 ^oC) is possible to occur. The high temperature during a long summer will affect also the relative air humidity. Therefore several considerations concerning the storage of raw materials and products, and building constructions in general to cope with a wide temperature range must be made. In addition to it, operators clothing including protective equipment must as well be correspondingly considered.

3. *Threat through instability in political situation*. Germany is considered as a country with a relative high stability in political condition. This point of concern is taken to be irrelevant for the analysis.

4. *Regulations and laws in construction projects, safety, health and environment*. All aspects in regulations and laws applied in European Union, in Germany and in the federal state of Hessen concerning construction projects of chemical plants must be thoroughly learned and performed.

5. *Official public holidays and festive days*. Since in Germany there are no particular holidays, on which production must be stopped, this point will be irrelevant for the analysis.

6. *Differences in cultural backgrounds, symbols and applied measurement units.* There is a relative wide range of difference in cultural backgrounds among the society living in Germany. Consequently, there is a high probability that the workforce available to be recruited by the company have different cultures. Not only the difference in tradition that should be concerned in recruiting workers with different cultural backgrounds, but also their custom in understanding symbols and units used in plant operation. Hence, the use of symbols, colours, marks and codes based on EU standards must be ensured, and the operators must be acknowledged about this concern. Other important issue is the use of German as the only official language during work, even if they are working with other people who speak the same mother language.

7. *Workforce/manning availability*. In the industrial complex where the new plant is located, it is assumed that reliable workforce can be obtained from an educational institution owned by the complex. The students are educated with relevant backgrounds required by various industries in the complex, while they are also obligated to conduct practical work in the corresponding industry during their study. However, more senior workers with more experience and better qualifications are required in the operation. Since the company also has many other plants at the same location and some of those plants have basic similarities with the new plant being designed, the availability of experienced and qualified workers is not a concern.

The next step of HFAD-Conceptual after developing the "Preliminary HFD-catalogue" is the performance of functional analysis and the allocation of functions. For the purpose of this case-study, only the "Mixing Process" will be taken under analysis, which will be responsible to prepare the raw materials before going further into the reaction and purification stage later on. The mixing process involves 5 smaller parts: charging of solid materials, charging of liquids, pre-treatment of additives and solvents, mixing in a stir tank, and suspension grinding (Table 6. 1), while the basic block diagram of the process is shown in Figure 8. 1.

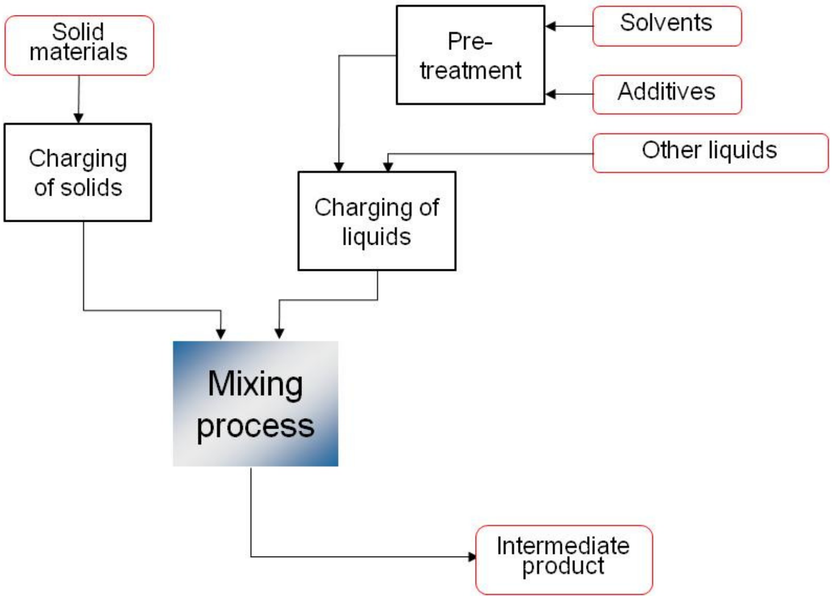

Figure 8. 1 Basic block diagram of the "Mixing Process"

Table 8. 1 Example of a *Preliminary HFD-Catalogue*

Relevant conditional aspects		***HF design considerations***
I.1	Climate and geographical conditions	Not relevant
I.2	Extreme weather and environmental constraints	Due to possible extreme temperatures (in winter and in summer) and high air humidity in summer: 1. Design of storage and warehouse (especially for solid materials and gasses). For solids delivered in big-bags or sacks: avoid mix-up through sufficient procedural and inventory systems 2. Delivery scheduling and quantity (sizing of packaging) 3. Design of working and protective clothing for seasons with both extreme high and low temperatures 4. Safety equipment correspondingly (if the use of protective clothing was unlikely due to extreme weather)
I.3	Threat through instability in political situation	Not relevant
I.4	Regulation and laws on safety, health and environment	Consider all applied laws and regulations concerning constructions project of the exact type of industry and safety requirements within: 1. The European Union 2. Germany 3. Federal state of Hessen
I.5	Official public holidays and festive days	Not relevant to operating hours and production activity
I.6	Differences in cultural backgrounds, symbols and applied units	Use of the international standards of measurement units (ºC, kg, m, bar, etc.), and inform the workers from diverse regions about this issue
		Use of the EU standards to design labels and signs, including marking, coding and colouring of different operating elements

		Concerning a big range of cultural backgrounds: 1. Assure the use of German as the only official language within site and during work 2. Infrastructures availability to facilitate different needs (e.g. religion background)
		Considerations on team formation based on possible social conflicts and frictions among workforce with different cultural backgrounds
I.7	Workforce/manning availability and qualifications	Recruitment of workforce graduated from education institution supported by the industrial complex where the plant is located
		Besides academic background and working experience, German language proficiency must be set as a primary requirement

Functional analysis will identify the intention that must be achieved by each process part, so that afterwards, careful consideration can be made in allocating the functions, either completely to machine (automated), to human operator (manual) or to both (semi-automatic). For this case-study, the information concerning all functions is provided in Table 8. 2. The first identification of operator involvement to fulfil manual and semi-automatic functions is conducted subsequently, based on the classification of task types. The identification of task types can use information coming from the "Preliminary HFD-catalogue".

For instance, the process part "charging of solid materials": after considerations proposed in the catalogue (Table 8. 1), due to possibility of high air humidity at plant location, it is very unlikely to store hygroscopic solids in a bulk without extra technical equipment that can guarantee the flow of materials to the process. Since the design is still too premature to decide the exact feasible technology to apply, several options must be thought of. As far as applicable, solids can be dissolved in certain solvent, or one less problematic option from technical point of view will be to have the solids delivered in sacks or big bags with the capacity suitable for every batch, and to have the operators charge those solids manually through a chamber. Both options have its pros and cons, depending on the design prerequisites. However, recognizing the options will help to allocate the functions and to correspondingly identify the possible operator contribution to achieve the intention.

Table 8. 2 Functional analysis and allocation of functions for every process part of the "Mixing Process"

Process part		*Functions*	*Allocation*	*Type of tasks*	*Remarks*
P1	Charging of solid materials	Feeding the exact types and amount of solid materials required for mixing process into stir tank	Semi-automatic or manual	Preparation and operation	Avoid confusion and mix-up of (big) bags
P2	Charging of liquids (including additives & solvents)	Feeding the exact types and amount of liquids required for mixing process into stir tank	Semi-automatic or manual	Preparation and operation	
P3	Pre-treatment of additives & solvents	Pre-heating or preparation of certain additives & solvent and intermediate storage in a buffer tanks	Semi-automatic	Process start-up/ shut-down	In some cases can involve mixing of additives with the solvents
				Monitoring & controlling	
				Testing, sampling & inspection	
P4	Mixing in a stir tank	Producing suspensions that meet desired specifications	Semi-automatic	Process start-up/ shut-down	
				Monitoring & controlling	
				Testing, sampling & inspection	
P5	Suspension grinding	Reducing particle size in suspension down to certain tolerable range	Semi-automatic	Process start-up/ shut-down	
				Monitoring & controlling	
				Testing, sampling & inspection	

The results delivered by the "Preliminary HFD-catalogue" (Table 8. 1) and through functional analysis (Table 8. 2) are provided for the design team for the next development, so that the design achieved will not only meet technical requirements but address also the HF concerns.

HF-Design Evaluation in Conceptual Design

HF evaluation of the current state of the design must be iteratively performed, in order to make sure that none of the design requirements from HF perspective was unfulfilled. For this purpose, the evaluation form provided in Figure 7. 16 assists the recognition of necessary changes on the ongoing design up to the recent time. After the evaluation yields satisfactory results, the design team can recommend the process to proceed into basic engineering.

For the case study, the evaluation is demonstrated in Figure 8. 2. The design of various HF relevant aspects is evaluated in terms of their status in meeting different design requirements. Those unrelated design requirements are blocked on the evaluation form, and are not necessary to be rated. Only the blank fields must be filled-in with a score between 0 and 3 as defined in Table 7. 2.

The one-time evaluation for this case-study (Figure 8. 2) shows that there is still a need to several design aspects (marked with either colour yellow or red). One example of design consideration marked with yellow is the transport of materials and products, which is rated with '2' in its relation with 'to handle extreme high/low temperature'. This expresses that the design team had taken the possible extreme temperature into account in planning the means for transportation between warehouse and the plant, and had considered that an operator might have to contribute in this activity, but at the time the evaluation was taking place, they have not yet decided how the transport of materials will run under extreme temperature. The yellow mark will remind the design team that there are still several considerations to be paid attention to.

'Safety clothing and equipment' in this example is marked with the colour red, which means that the design of this aspect still has a score "3" representing its status in meeting various design requirement. In this case, there is a bigger urge for the design team to look back to what has not been taken into account in the design concepts and has not been realized yet. The evaluation must be iteratively conducted until there is no design consideration is marked with red. If some of the considerations were still marked with yellow, and to a certain extent the design team believed that no further effort can be done at the time being, then the design can proceed only with a reminder that the unfinished HF activities still need to be completed during the next stage.

Evaluation Form

HFAD in CONCEPTUAL Design

Analysis of HF aspects design related to geographical condition of selected plant location

No.	HF Design Considerations	No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Mean SCORE	*Remarks*
			Climate & geographical condition					*Extreme weather constraints*			*Instable political situation*		*Regulation on safety, health & environment*			*Official holidays & festive days*			*Difference in cultural background, symbols & units*					*Workforce Avail. & qualifct.*			
		Design Objectives	Use of guidelines (e.g. whole building design guidelines and regulation)	Earthquake proof design	Landslide proof design	Resistance to exposure through volcanic activities	Storm, tsunamis and flood resistance	To handle extreme high/low temperatures	To handle high air humidity	To solve problems with water supply (irregular periods of dry season)	Consider damages through attacks or vandalism	*… (add, depends on the specific case)*	EU standards	Guidelines of the German Hazardous Incidents Commission	Guidelines for technical & engineering work in Hessen	Consider days where production is not allowed to run	Consider days where operators are not allowed to work	*… (add, depends on the specific case)*	The use of SI units as measurement unit	Different familiar symbols in labeling & signage among workforce	Different familiar colors, markings & codes among workforce	Diverse spoken languages among workforce/ society in general	Consider hierarchical structure in social life & other cultural constrains	Required experience	Required qualifications		
S1	Design of warehouse and storage		x 1	x 0	x 0	x 0	x 0	x 1	x 1	x 0	x 0		x 1	x 1	x 1											0.5	
S2	Adjustment of building construction (to cope with geographical condition)		x 1	x 0	x 0	x 0	x 0				x 0															0.17	
S3	Design of plant layout		x 2	x 0	x 0	x 0	x 0		x 2																	0.67	
S4	Transport of materials and products							x 2	x 2	x 0	x 0															1	
S5	Safety clothing and equipment							x 3	x 2	x 0																1.67	
S6	Water supply sufficiency							x 0	x 0	x 0																0	
S7	Temperature control system							x 1	x 1	x 0																0.67	
S8	Emergency exit & evacuation way										x 0															0	
S9	Design consideration based on applied regulations and law												x 1	x 1	x 1											1	
S10	Shifting plans															x 0	x 0									0	
S11	Production plans															x 0	x 0									0	
S12	Work scheduling and assignment of works															x 0	x 0									0	
S13	Use of the same units on the whole design												x 1	x 1	x 1				x 1	x 1	x 1	x 1	x 0			0.88	
S14	Design of labels and signs												x 2	x 2	x 2				x 2	x 2	x 2	x 2	x 0			1.75	
S15	Marking, coloring and coding of labels, signs, information display												x 2	x 2	x 2				x 2	x 2	x 2	x 2	x 0			1.75	
S16	Use of a unique language																		x 1	x 1	x 1	x 1	x 0			0.8	
S17	Team formation																		x 2	x 2	x 2	x 2	x 0			1.6	
S18	Consideration to outsource																							x 0	x 0	0	
S19	Training and courses																							x 2	x 2	2	

Figure 8. 2 HF-Design Evaluation in Conceptual Engineering

8.2 Basic Engineering

As the design proceeds further into basic engineering phase, more decisions should have been taken by the design team concerning the basic process requirements. With the inputs coming from design team, in basic engineering an analysis of operator tasks will be performed by means of HFAD-Basic. In this case-study, two process parts are going to be analysed closer, these are the "P1: Charging of solid materials" and the "P4: Mixing in a stir tank". In Table 8. 3, a more detailed analysis of tasks to be conducted by operators is exemplified, which includes tasks identification, description concerning the characteristics of each task, and the possible workload that can be arisen during the performance of those tasks.

Table 8. 3 Task analysis by means of HFAD-basic

Process part		***Type of tasks***	***Operator tasks***	***Task characteristics***	***Relevant aspects***		***Remarks***
P1	**Charging of solid materials**	Preparation and operation	Transporting materials in bags from warehouse and arrange them on charging location	Can lead to confusion, wrong materials are taken	II.1 II.2 II.4 II.5	Material properties Warehouse & storage Working environment Accessibility	Distant location of warehouse can accumulate workload Insufficient procedural system can cause confusion and mix-up
			Charging the solid materials in bags into the chamber manually	Can be very physically hard, can require the use of additional working tools	II.1 II.2 II.3 II.4 II.5 II.7	Material properties Warehouse & storage Manual handlings Working environment Accessibility Additional tools	High physical load and potential to cause hazard to health
P4	**Mixing in a stir tank**	Process start-up/ shut-down	Starting and ending the batch	In control room	II.6	Operating interface	
		Monitoring & controlling	Monitoring of process parameters	In control room	II.6	Operating interface	

			Cross-checking in field	In field	II.4 II.5 II.6	Working environment Accessibility Operating interface	
		Testing, sampling & inspection	Density control	In control room	II.6	Operating interface	
			Sampling	Can lead to material release,. Can lead to exposure, hazards and injuries to operators	II.1 II.3 II.4 II.5 II.6	Material properties Manual handlings Working environment Accessibility Control and monitoring system	Distant location of laboratory and absent of sampling tools can accumulate physical load and stress

In this design stage, there are 8 HF aspects relevant to operators' contribution and responsibility during process operation, as listed previously in Figure 7. 3. These aspects can have influence on operators' performance during work, yet not all might have an effect on every task performance. For instance, during the charging of solid materials in bags into stir tank (P1, task number 2), only 6 of all aspects are considered to be relevant in giving influence on the operators. These are the aspects to be designed with additional considerations concerning HF, to ensure that the system design eliminates unrealistic demands on human operators through the availability of sufficient support they require in completing the work. The questionnaires in Figure 7. 5, as well as Figure 7. 7 to Figure 7. 14 will assist the analysis of all relevant HF aspects to each task performance, whose results will be summarized in the "HFD-catalogue-Basic".

Table 8. 4 HFD-catalogue in basic engineering (applied only to P1 and P4)

Relevant aspects		***Tasks***	***HF design considerations***
II.1	Material properties	Transporting materials in bags from warehouse and arrange them on charging location	Consideration to improve inherent safety through minimization, substitution, moderation or simplification
			Dealing with hazardous/dangerous materials: avoid direct contact (automation), adequate protective clothing, reachability of first aid and emergency safety equipment, labelling and signage, working procedure and manuals
			Adequate design of work place and plant layout
		Charging the solid materials in bags into the chamber	See above

		manually	
		Sampling	See above
II.2	Storage of raw materials and products	Transporting materials in bags from warehouse and arrange them on charging location	If up to this point no separated area for dangerous materials is available: modification on building construction to avoid dangerous potentials required
			In relation to extreme weather condition (see point I.2): Extra attention to sudden temperature change during operation, building construction to avoid over-/underheating of stored materials
			Possible reaction / contamination between materials to be transported: to be transported separately
		Charging the solid materials in bags into the chamber manually	See above
			For temporary storing at work location: adequate space availability, avoid reversed charging order if necessary, working procedure, work design (scheduling to transporting materials from warehouse) to minimize humidification effect.
II.3	Manual handlings of materials, product and equipment	Charging the solid materials in bags into the chamber manually	Partial automation with sufficient operator supporting system
			Full protective clothing, full-face mask, adequate ventilation
			Task with potential physical load, involves pulling, pushing, lifting: 1. Consider guidelines and the recommended weight limit (RWL) 2. Pulling under instead of putting up heavy objects 3. Reduction of lifting height (use of lifting device/table, limited height of piles of bags on palette, etc.) 4. Reduction of lifting frequency (adjusted work design) 5. Avoidance of awkward positioning (equipment arrangement, reachability of necessary tools and operating elements) 6. Space availability for work in comfort and safe maneuvering
		Sampling	Not necessarily to be automated for liquid and solid. Sampling of gas must be automated.
			Protective clothing, breathing mask, gloves, adequate ventilation
			1. Procedures (form, checklist) 2. Reachability of necessary tools and sampling materials 3. Reachability of operating elements (valves, buttons, etc.), avoid awkward positioning 4. Labelling and signage 5. Space availability
II.4	Working environment	Transporting materials in bags from warehouse to charging location	Task is to be performed in the beginning of every batch (on day and night shift): 1. Adequate lighting for night shift between plant and warehouse, on-site, and in the warehouse 2. Avoid glare, blinding and reflection. Adequate light distribution between indoor and outdoor
			Under low intensity noise: ear protection only if required
			Consideration on the limit of heat exposure and comfort health index.
			Since warehouse is located separated from plant building: consider necessary vehicles or other transport devices and possible workload through the use of those devices

			Not to be done under vibration
		Charging the solid materials in bags into the chamber manually	Task is to be performed in the beginning of every batch (on day and night shift): 1. Adequate lighting for night 2. Avoid glare, blinding and reflection. Adequate light distribution between indoor and outdoor
			Noise: 1. Dampening of noise at the source (i.e. roller crusher or neighbouring equipment) 2. Compulsory use of ear protection 3. Reduction of time span at location (i.e. split/rotate the work with another operator, work design)
			Temperature: 1. Consider heat exposure from related and neighbouring equipment. 2. The work itself can be physically hard, can affect body temperature. 3. Reduction of time span at location (i.e. split/rotate the work with another operator, work design)
			Vibration: 1. Reduction through compatible technology 2. Reduction of time span at location (i.e. split/rotate the work with another operator, work design)
II.5	Accessibility	Transporting materials in bags from warehouse to charging location	Work space arrangement: consider guidelines and regulations, equipment sizing between 5 – 95 percentile, adequate spacing for task completion, accessible emergency exit and evacuation way
			Consideration on the requirement for adequate work space under limitation of anthropometric data, equipment arrangement under consideration that operators use extra clothing and additional tools
			Labelling and signage
			Intercommunication system, emergency alarm, emergency exit, and evacuation way both in warehouse and at charging location
		Charging the solid materials in bags into the chamber manually	See above
			Avoidance of direct contact with heated equipment
		Sampling	See above
			Accessible sampling location and necessary equipment, shortest pathway to laboratory or examination location
II.6	Operating interface/ Man-machine interface	All monitoring and controlling tasks in control room (separated analysed)	The analysis of control room tasks and the corresponding control room as well as its control system configuration requires other systematic methodology
II.7	Additional supporting tools	Charging the solid materials in bags into the chamber	Selection of operating elements for task with high physical load, lifting devices/table
			Positioning of process elements/equipment to be lifted/removed manually : optimal height and distance

		manually	Weight of the supporting tools, user friendliness, not indicating potential harms to operators (such as the use of a knife or unstable heavy devices)
			Labelling and signage, availability of feedback
II.8	Control and monitoring	Flowing solvents and additives into stir tank	Operator is required to open and look into the tank to ensure the flow: Use sight-glass with adequate lighting
			Equipment placement and layout, adequate access for maneuvering
			Observation of process parameters at location (cross-checking with control room operators): accessible/reachable/readable parameter display, assure the use of the correct measurement unit, adequate lighting
			Labelling
		Sampling	See above

HF-Design Evaluation in Basic Engineering

The design considerations tabulated in HFD-catalogue-Basic shown in Table 8. 4 will as well be provided for the design team to ensure that the process design will not be taken farther into detail engineering, without realizing the crucial requirements to cope with HF issues that might arise during operation. Changes in detail engineering of these aspects will cost more time and effort; with much less space for improvement left and only minor changes may still be possible to be made upon. Hence, a careful evaluation must be made in order to make certain whether the system design has satisfactorily addressed HF in every aspect before going to the next stage.

For this case-study, a one-time evaluation was performed using the evaluation form provided in Figure 7. 17, and the result to this evaluation is presented in Figure 8. 3. At the time the evaluation was conducted, there is still a number of design considerations marked with colour red and yellow. The design team must look back to each of those HF design considerations and the associated design requirements to at the least eliminate all the red marked ones, before proceeding to detail engineering.

8.3 Detail Engineering

In detail engineering phase, the process design is to be finalized from all angles, including technical, organisational as well as from human factors perspective. By making use of the result coming from the HFAD-Basic, the design team has been provided with design suggestions concerning every HF relevant aspect and the necessary HF issues that might arise during operation. With more process information available in this stage, HF design analysis can be performed in more detail.

As the project enters detail engineering, safety reports must have been made available to meet regulations requirement. In Germany, safety analyses of process and plant design is required to be performed qualitatively, mostly conducted by means of HAZOP analysis. During the performance of HAZOP, HF considerations cannot be taken aside, since some possible deviations identified in HAZOP might have been caused through operator incorrect actions, or might need operator corrective actions to bring the process to its normal operating state. The tasks where errors with significant effects are possible to happen or can cause process deviations, tasks where harm to operators is possible to arise, and tasks with particular characteristics that can overload the operators are to be considered as 'critical' with a need of further analysis. Therefore, the first step of HFAD-Detail will be the performance of a HAZOPA, which is afterwards followed by a development of an "HFD-catalogue-Detail" to address the most necessary improvements that still need to be made upon the design.

In this case study, the task P1.2 "Charging the solid materials in bags into the chamber manually" (see Table 8. 3) is analysed further by means of HFAD-Detail. After the decision to not automate the task due to some technical and financial reasons, the charging of solid materials is to be done manually by operators, as it is normally conducted in a similar process plant owned by the company. Learning from experience in the existing similar plant, the engineers are aware that in the new plant, design improvements must be conducted, since the work is too dangerous and injurious for the operator who performs it. This experience can give better insights when used systematically in HFAD-Detail.

The analysis through HFAD-Basic on this task has pointed out several concerns related to material properties, warehouse & storage, manual handlings, working environment, accessibility and the use of additional tools as listed previously in the "HFD-catalogue-Basic" (Table 8. 4). Since the design team has now taken all of the considerations provided by the catalogue into account during design optimization, several possible errors recognized in the earlier HAZOPA analysis in Chapter 6 (without HF consideration during design) can be prevented. Possible errors during performance of this task that are now avoided through the current design are among others:

Evaluation Form

HFAD in BASIC Design

Analysis of HF aspects design related to operators' contribution and responsibility

No.	HF Design Considerations	Related to tasks: Task	Design Objectives	1 Considering the use of flammable materials	2 Considering the use of explosive/deflagrativ materials	3 Considering the use of highly reactive materials	4 Considering the use hazardous materials : toxic, corrosive, irritating	5 To handle extreme high/low temperatures	6 To handle high air humidity	7 To solve problems with water supply (irregular periods of dry season)	8 Considering limitations for storing together with other materials	9 Allowing temporary storing at work location	10 Considering the form of materials to be handled manually (solid, gas or liquid)	11 Avoiding hazards to people during handling	12 Ensuring high precision	13 Ensuring speed (fast movement)	14 Supporting monotonous frequently repeated movement	15 Supporting tasks with high physical load	16 Supporting tasks requiring lifting, pulling, pushing positioning	17 Considering suitable guidelines	18 Support task completion on day shift	19 Support task completion on day & night shift	20 Protection from excessive noise	21 Protection from heat exposure at location	22 Protection from excessive vibration effect	23 Support tasks requiring movement between buildings/plant/parts	24 Providing adequate space for task completion & for temporary material storing	25 Allowing movement and maneuver under the use of protective clothing & equipment	26 Allowing movement between heated equipment	27 Coping with possibility of fire, explosion or material release	28 Adequate space for manual handlings	29 Allow maintenance, repair and service	30 Support field operators during startup	31 Support control room operators during startup	32 Ensure correct data inputs	33 Work in standing position	34 Work in sitting position	35 Support work facing a display/console/ control panel	36 Allowing fast response	37 Allowing high precision	38 Ease tasks requiring physical power	39 Support tasks dealing with inadequate reaching distance	40 Reachable positioning of necessary equipment	41 Operating element with adequate supporting characteristics	42 Support field monitoring with possible direct contact with materials or equipment	43 Support field monitoring with NO possible direct contact with materials or equipment	44 Provide support for parameter monitoring and controlling	Mean SCORE	Remarks
				Material properties				Material storage & warehouse					Manual handlings								Working environment					Accessibility							Operating interface/ Man-machine interface						Operating elements & additional supporting tools						Process monitoring				
S1	Design of warehouse and storage																																																
S2	Adjustment of building construction (to cope with geographical condition)	P1.1 / P1.2						x 1																																								1	
S3	Design of plant layout	P1.1 / P1.2 / P4.3		x 1	x 1	x 1	x 1																																									1	
S4	Transport of materials (from & to plant location)	P1.1 / P1.2																																															
S5	Protective clothing and equipment	P1.1 / P1.2 / P4.1 / P4.2 / P4.3					x 1																						x 2	x 1																		1.33	
S6	Water supply sufficiency									x 0																																						0	
S7	Temperature control system						x 1																																									1	
S8	Emergency exit & evacuation way	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																										x 2		x 1																		1.5	
S9	Design consideration based on applied regulations and law	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																																															
S10	Shifting plans																																																
S11	Production plans																																																
S12	Work scheduling, rotation, assignment of works	P1.1 / P1.2										x 3												x 2																								2.5	
S13	Use of the same units on the whole design	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																																	x 1												x 1	1	
S14	Design of labels and signs	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																				x 1	x 1																				x 1				x 2	1.25	
S15	Marking, coloring and coding of labels, signs, information display	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																				x 1	x 1																				x 1					1	
S16	Use of a unique language	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																																															
S17	Team formation																																																
S18	Consideration to outsource																																																
S19	Trainings and courses																																																
S20	Amount reduction of dangerous materials	P1.1 / P1.2 / P4.1 / P4.2 / P4.3		x 1	x 1	x 1	x 1																																									1	
S21	Substitution of dangerous materials	P1.1 / P1.2 / P4.1 / P4.2 / P4.3		x 0	x 0	x 0	x 0																																									0	
S22	Effect moderation	P1.1 / P1.2 / P4.1 / P4.2 / P4.3		x 1	x 1	x 1	x 1																																									1	
S23	Design simplification	P1.1 / P1.2 / P4.1 / P4.2 / P4.3		x 1	x 1	x 1	x 1																																									1	
S24	Accessibility (point II.5); reachablility, pathway	P1.1 / P1.2 / P4.1 / P4.2 / P4.3		x 1	x 1	x 1	x 1	x 1	x 1	x 0	x 1	x 3														x 3	x 3																		x 2			1.5	
S25	Avoidance of contact with hazardous materials	P1.1 / P1.2 / P4.1 / P4.2 / P4.3					x 1																																									1	
S26	Contact time minimization	P1.2 / P4.2 / P4.3					x 2																																									2	
S27	Degree of automation (man-machine allocation)	P1.1 / P1.2 / P4.1 / P4.2 / P4.3					x 2	x 2	x 0	x 0	x 0	x 2		x 1	x 1	x 1	x 1	x 2	x 2	x 2				x 3																								1.36	
S28	Emergency safety equipment: Eye-wash, shower, staging area, evacuation way, etc.	P1.1 / P1.2 / P4.1 / P4.2 / P4.3					x 1	x 1	x 0	x 1	x 1	x 1																																				0.83	
S29	Feed stroke & route of transport	P1.1 / P4.3						x 2	x 0	x 2	x 2	x 2																																				2	
S30	Monitoring of temperature change	P1.1						x 1																																								1	
S31	Emergency alarms & fire services							x 1		x 1																																						1	
S32	Cooling system									x 1																																						1	
S33	Drying/dehumidification process	P1.1 / P1.2							x 1																																							1	
S34	Corrosion avoidance								x 1																																							1	
S35	Identification of possible reactions between materials					x 1					x 1																																					1	
S36	Warehouse location	P1.1 / P1.2		x 1	x 1	x 1	x 1				x 1																																					1	
S37	Full protection clothing, full face mask	P1.1 / P1.2 / P4.1 / P4.2 / P4.3											x 1																																			1	
S38	Waterproof protection clothing	P4.2 / P4.3											x 1																																			1	
S39	Ventilation	P1.1 / P1.2 / P4.1 / P4.2 / P4.3							x 1				x 1																																			1	
S40	Leakage identification system												x 1																																			1	
S41	Operator supporting system in field	P1.1 / P1.2 / P4.1 / P4.2 / P4.3												x 2	x 0	x 0	x 2	x 2	x 2	x 2																												2	
S42	Operator supporting system in control room	P4.2 / P4.3												x 0																																		0	
S43	Consideration on design parameters based on guidelines for ergonomics	P1.1 / P1.2 / P4.1 / P4.2 / P4.3													x 1	x 1	x 1	x 1	x 1	x 1																												1	
S44	Pull under position instead of put up	P1.1 / P1.2 / P4.3																x 1	x 1	x 1																												1	
S45	Lifting height	P1.1 / P1.2 / P4.3																x 2	x 2	x 2																												2	
S46	Lifting frequence	P1.1 / P1.2																x 2	x 2	x 2																												2	
S47	Avoidance of awkward positioning	P1.1 / P1.2 / P4.2 / P4.3																x 2	x 2	x 2																												2	
S48	Comfortable positioning to maneuver	P1.1 / P1.2 / P4.3																x 2	x 2	x 2																												2	
S49	Packaging dimensioning	P1.1 / P1.2																x 2	x 2	x 2																												2	
S50	Avoidance of glare, blinding and reflection	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																			x 1	x 1																x 1										1	
S51	Adequate lighting	P4.2 / P4.3																			x 1	x 1																							x 2		x 2	1.5	
S52	Use of ear protection	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																					x 1																									1	
S53	Noise dampening, sound absorption	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																					x 1																									1	
S54	Time span reduction at location	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																					x 2		x 2																							2	
S55	Blocking of access to source of noise	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																					x 1																									1	
S56	Air conditioning	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																						x 2																								2	
S57	Reduction of excessive energy usage	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																						x 1																								1	
S58	Re-allocation of work to other shifts	P1.1 / P1.2 / P4.3																						x 0																								0	
S59	Vibration reduction	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																							x 1																							1	
S60	Dimensioning of equipment and furnitures	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																									x 1				x 1	x 1				x 2	x 2											1.4	
S61	Equipment arrangement, workspace adequacy	P1.1 / P1.2 / P4.1 / P4.2 / P4.3										x 1															x 1				x 2	x 2													x 3			1.8	
S62	Means for movement; vehicles, transport device	P1.1 / P4.3																								x 1											x 1											1	
S63	Access to intercommunication system	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																												x 2																		2	
S64	Sampling location and equipment	P4.2 / P4.3																								x 2				x 2	x 2																	2	
S65	Information readability	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																			x 1	x 1											x 1														x 1	1	
S66	Placement of operating elements, reachability	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																															x 1															1	
S67	Grouping of elements with similar functions	P4.1 / P4.2 / P4.3																															x 1															1	
S68	Illumination of labels and signs displaying extra important information	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																			x 1	x 1											x 1															1	
S69	Consistency of information display	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																															x 1															1	
S70	Avoidance of confusion and mix-up	P1.1 / P1.2 / P4.3										x 1																					x 1															1	
S71	Control room location	P4.2																								x 1								x 1														1	
S72	Control room dimensioning	P4.2																																x 1														1	
S73	DCS Design	P4.2																																x 2														2	
S74	Data availability for inputting set-points	P4.2																																x 2	x 2													2	
S75	Display configuration	P4.2																																x 2				x 2										2	
S76	Control room lighting	P4.2																																x 1	x 1			x 1										1	
S77	Correct selection of operating elements	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																															x 3	x 3	x 3				x 3	x 3	x 3	x 3		x 3				3	
S78	Dimensioning of operating elements	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																															x 3	x 3		x 3	x 3							x 3				3	
S79	Positioning & placement of operating elements	P1.1 / P1.2 / P4.1 / P4.2 / P4.3																															x 3	x 3	x 3	x 3	x 3	x 3					x 3	3				3	
S80	Feed-back availability	P4.2																															x 3	x 3	x 3				x 3	x 3							x 3	3	
S81	Design & configuration of control room	P4.2																																x 2		x 2									x 2	x 2		2	
S82	Covering & containment of process equipment	P4.2																																											x 1			1	
S83	Design of sight-glass	P4.2																																											x 1			1	

Figure 8. 3 HF-Design evaluation in basic engineering

1. Mistakes conducted during transfer of the palette with bags of solid materials approaching the charging chamber due to insufficient available space. The arrangement of neighbouring equipment has been adjusted to provide the operator with adequate space for manoeuvring. Through this redesign, possibility of bags falling off the pile that can cause material release and injuries is minimized.
2. Mistakes conducted as the operator lifts each bag off the palette onto the chamber grid (sieve). Work design has been adjusted to reduce the size of bags or sacks to be lifted by one operator, and the accumulated maximum weight one operator is allowed to lift within a certain time frame. Consequently, for a mixing process that requires bigger amount of solid materials, the work must be split between 2 operators rotationally. Additionally, the use of lifting device and scissor-lift with rotating table to position the sacks at work height instead of on floor level also reduces operator load and hence, reduces the likelihood of the occurrence of errors and injuries.
3. The use of an uncovered sharp tool such as a knife is substituted with other cutting device, such as safety cutters for smaller sacks, or by asking the supplier to deliver the material in open-mouth sacks. In other case, if a very big amount of solid materials is required to be fed daily, a use of an automatic sack opener or bag splitter should be considered.

However, even though many of the possible errors have been avoided through design improvement, other errors may still arise through the introduction of the new solution offered by the design team. For this reason, the HFAD-Detail must be implemented to prove whether other possible errors with significant effects on process state can arise under the current working condition. The generation of "HFD-catalogue-Detail" is facilitated through the use of modified PITOPA questionnaire for PIFs evaluation, which will point out the aspects in need of improvement that must be carried out before the design is brought under construction. At this point it is very important to include worker's opinion and experience into the analysis, and as far as practicable to also perform a virtual simulation of the work together with worker representatives. The feed-back coming from operator's side is a very crucial additional input for the design team in optimizing the plant design, including the job design, the development of working procedures as well as the design of training programmes.

The questionnaire to be used for an analysis in detail engineering is provided in Appendix A. The use of this questionnaire to generate HFD-catalogue-Detail provides at the same time a means to conduct the design evaluation. If no considerably important changes must be made, the design can continue to construction phase, during which a pre-startup safety review (PSSR) should be performed as a final check (CCPS, 2007a).

This new HF design approach needs to be computerized to better assist the consideration of HF in plant design and to cope with the huge amount of data. This computer program must be able to automatically summarize all information collected during HF design and list every HF aspect to be concerned of, in order to optimize the design in achieving a safe operation. The application of this program must be done iteratively throughout the design, so that necessary modifications can be comprehended as early as possible and eventually, a regularly repeated HF analysis by means of PITOPA must be performed during process operation to maintain the HF quality of the plant.

Moreover, although the HFAD can provide design suggestions related to HF issues for all types of human activities in a process plant, for tasks conducted in control room (supervisory control tasks) the suggestions out of HFAD are still considered too general and refers directly to the utilization of available guidelines for designing control system and alarm system. Even though reliable guidelines are available, the utilization of which must be made based on operators requirements in a particular process plant. Therefore, an analysis of operator actions during the performance of control and monitoring tasks is necessary to be conducted separately from the analysis of other manual tasks conducted in field.

CHAPTER 9

APPROACH FOR IMPROVING OPERATOR PERFORMANCE IN CONTROL ROOM

The introduction of DCSs (Distributed Control Systems) in process industry has led to a significant shift of operators work and responsibilities in control room as previously discussed in Chapter 2.4.2. The increasing degree of automation and complexity of process plants also enhances the requirements on operators in monitoring and controlling process flow. The large number of sub-processes interconnected with one another has a consequence that disturbances are no longer tend to occur in isolation (Stanton, 1994). Unlike during performance of field tasks, control room operators are assigned with a kind of workload that requires different levels of concentration and decision making ability. Therefore, the presence of sufficient knowledge and a comprehensive understanding about the process is required.

Automation and computer control create a distance between operators and the process. As a consequence of one essential reason of automation, there is a reduction of operator's direct involvement in the actual processes. This leads to a decrease of process understanding. Thus, they become more unaware of what is actually happening behind the displays, which can lead to a hesitation in deciding what to do and how to act during critical conditions. The fear of any fault arising during controlling and monitoring, dependent on the company safety culture, can increase as the operators know that incorrect action may lead to an accident or to an enormous economic value (Ivergard, et al., 2009).

Particularly during abnormal condition, control room operators are required to overcome with a huge amount of information while having to consider the accurate corrective action simultaneously. A mistake made in taking decision in such situation can trigger a series of events subsequently that might lead to a disaster. In providing the operators with adequate support, the understanding about how they react to disturbances and how different factors can affect their performance is very essential to have. Such an understanding can only be achieved through a proactive incorporation of

HF into the design of DCS by among others, performing an analysis on control room operator actions.

Unfortunately, the means that provides adequate systematic for incorporating HF considerations into the design of DCS is still lacking in process industries. The available methods to increase operator's situational awareness (SA) and to analyse cognitive tasks in control room (discussed previously in Chapter 3.5) are not giving much assistance in optimizing the design of DCS in process industries and hence, are not widely implemented. Several reasons that cause the slow penetration of such methods in process industries are:

- Most of the methods provide retrospective rather than prospective analyses. They provide a way to measure and analyse the level of SA or vigilance, yet, not focusing on finding solutions to improve the condition in avoiding undesired events.
- The methods to improve SA cannot specifically clarify how the avoidance of operator incorrect actions must address the adequacy of DCS-design. As example, methods like SAPAT and GOMS have their focus on the interaction between human and computer with little emphasis on the design and prioritization of alarms.
- The methods do not provide a systematic analysis to identify operator actions following an alarm (during upsets), the possible errors, or the consequences thereof. Moreover, there is no analysis on how the error occurrence can be interconnected one with another in generating a bigger incident.
- The methods do not enable the recognition of the most underlying problems in the system, and therefore are not leading to finding the exact solutions in avoiding operator errors in control room.

Meanwhile, although the method PITOPA-Design developed in this work (see Chapter 7) is aimed at the improvement of working condition in both field and control room tasks, the analysis by means of the new method can only provide general suggestions in relation with DCS design. Analysis of operator actions in control room requires a deeper scrutiny and must be conducted separately from the analysis of field tasks. In overcoming with various problems with control system, assistance from different guidelines is actually available. However, those guidelines for alarm design and management basically only provide recommendations to solve alarm problems without providing systematic approaches to reveal the underlying problems. Solutions recommended by the guidelines can only be properly selected and used if the exact underlying problems have been recognized. Hence, there is a need for a technique that provides a way to analyse what the system's deficiencies really are and what the operators are lacking of, to be able to extract the most suitable solutions from guidelines (Löwe, et al., 2010).

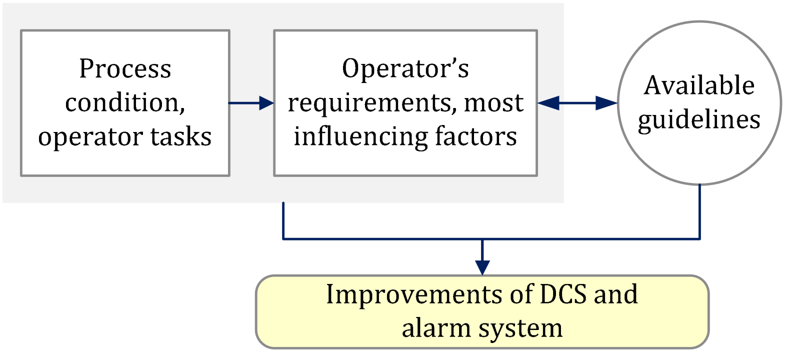

Figure 9. 1 The need of a technique to incorporate HF into design of DCS and alarm system

In this work, a method is developed to answer the call for a systematic integration of HF into DCS design that provides a way to reveal operators' needs in performing supervisory tasks in control rooms, and to exploit this information in designing the DCS, configuring control room and designing alarm system based on best practices and guidelines (Figure 9. 1). In developing the new method, which will be later referred to as the PITOPA-CR, a modification of PITOPA is carried out. The modification starts with a re-identification of performance influencing factors (PIFs) for supervisory tasks (work in control room), since these factors can differ from those that affect human beings during field tasks. Following the identification of control room PIFs, a modification of task analysis and operator actions analysis into the so-called Control Room Task Analysis (CRTA) technique, and the technique for Control Room Operator Actions Analysis (CROAA) will be conducted. Ultimately, the new method for analysing HF in control room will be integrated with the PITOPA-Design. A closer discussion about the development of the new approach is delivered in the following sections.

9.1 Performance Influencing Factors (PIFs) for Supervisory & Monitoring Tasks

To guaranty a reliable operator performance in a control room, there are two important parameters that must be developed and maintained, these are the vigilance level and situational awareness (SA). It is crucial to maintain operator's alertness during work, especially during process monitoring and supervisory tasks, where the work can be very monotonous. A high level of operator SA and vigilance, together with an optimal level of workload can lead to a reliable decision-making process and improve the overall operator performance (Stubler, et al., 1996; Hallbert, 1997).

All factors that can influence operator performance during supervisory or control tasks were identified in this work (Figure 9. 2) based on literature studies, several guidelines for control room configuration (Hallbert, 1997; O'Hara, et al., 2002; Stanton, et al., 2005), and most of all based on the previous works on PITOPA and field observation in the process industries. All of the identified PIFs have an influence on the vigilance level, workload, operators' SA and hence, on operator's final decision-making process, either directly or indirectly, in different ways and immensities. The relationship between each factor and these four parameters is very complex and cannot be easily modelled, since personal characteristics also play an important role in this interaction. A simulator-based study has once attempted to show the relationship between operator SA and subjective workload, but then discovered that the explanation of the relationship is more complicated, since many other factors including operator experience and team interaction can generally affect operator performance (Hallbert, 1997).

Despite of the difficulty to model the complex relationship between various PIFs and SA, vigilance and workload, the PIFs must still be identified at the very least. All of the identified PIFs listed in Figure 9. 2 hold the key to an optimal working condition in control room, and must be configured in such a way that eliminates unnecessary demand on operators. The factors describe not only the technical facility part of the system, but also the crucial aspects affecting human cognitive ability as well as the organisational aspects, these are: (a) Human-System/Human-Computer Interface, (b) Design of Control Room; (c) Workplace Design; (d) Job Design; (e) Operator Competence; (f) Operator Supporting System; (g) Alarm System and (f) Line Management.

An internal survey related to these control room PIFs was conducted at Bayer CropScience AG in Germany, in different plants owned by the company at the same location. The survey was undertaken by involving two groups, the operators and management personnel. The goal of this survey was to collect opinions from control room operators and plant managers concerning the relevance/importance of various PIFs in affecting supervisory and monitoring tasks. Results of the internal survey are presented in Figure 9. 3, whereas the actual values that represent the relative importance of every PIF in comparison with another (expressed also as weight of each PIF) is listed in Table 9. 1. The elicitation of weights for the control room PIFs took place by means of the AHP algorithm (see Chapter 2.7.1 for a closer explanation).

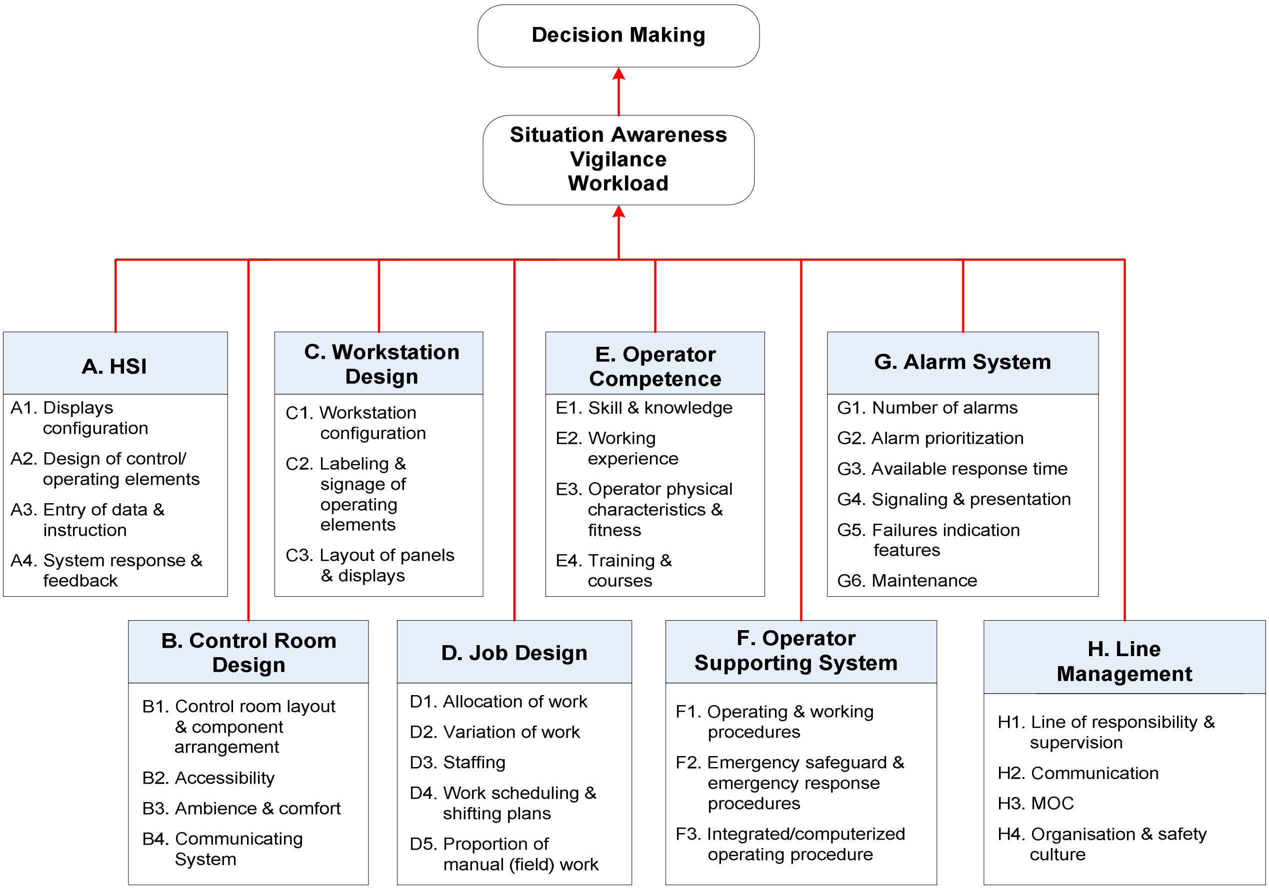

Figure 9. 2 Performance Influencing Factors in Control Room

Figure 9. 3 below shows the comparison between the attribute weights as rated by the operators (showed with green bars) and by the managers (orange bars) after their importance in influencing control room work. From this comparison, it is obvious that operators see the supervisory and monitoring work in control room as more demanding in terms of knowledge, experience and skill. Hence, they put the availability of proper and adequate operator supporting systems in form of an integrated operating system and emergency safeguard/response procedures at a relative high level of importance. At the next level, operators judged that the work in control room requires particular reliability in aptitude and physical fitness for duty. Operators can easily lose sight of process status just after a slight reduction of concentration level due to tired eyes, drowsiness or uncomfortable feel after being in a sitting position for hours.

Consequently, they see the availability of supports coming from diverse technical components as very important; these are the prioritization of alarms, adequate signs and labels of every necessary operating element, the assurance that all components are well maintained and the configuration of control room as a whole.

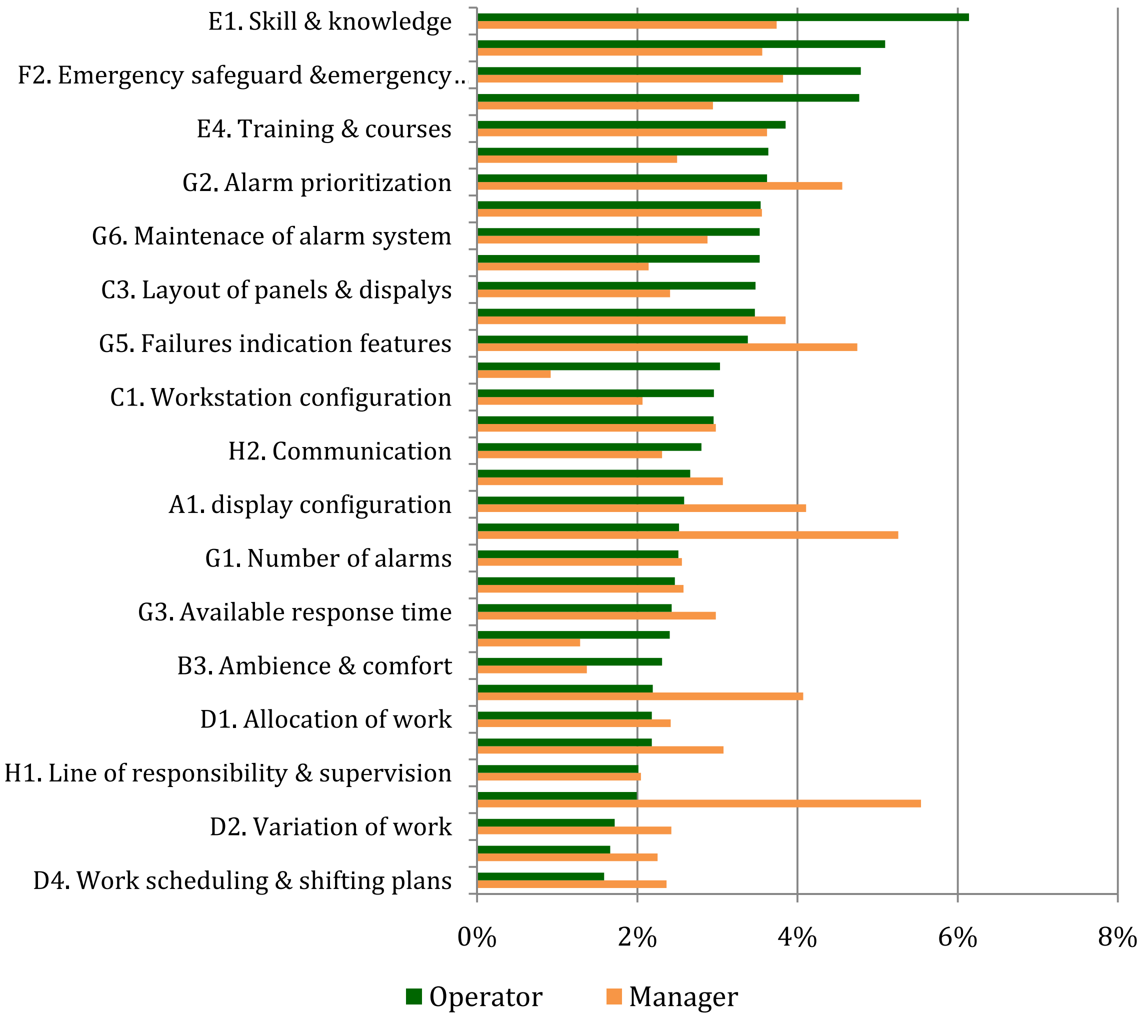

Figure 9. 3 Comparison between operators' & managers' judgement on the importance of HF attributes

In addition to the workstation and workplace design, the job design is also considered as a very important aspect to maintain their performance during supervisory tasks, especially staffing and the allocation of work. Many operators think that more often than it should, one shift is short of qualified workers for the operation. Such situation often occurs if most of the workers in one shift are already close to their retirement, and consequently receive more days-offs than the younger ones. On the other hand, the very young ones mostly still need to complete their training years and are not capable yet to work without direct supervision from a more senior one. The rest of the aspects are given a lower priority in terms of how immense they influence supervisory work, compared with other attributes. Nevertheless, once again it is to be noted that all factors identified here are important and can affect operator's work in control room. The fact that some of them are rated with lower degree of importance does not eliminate the must to consider all factors during design of process control system and control room design. The complete weighting system for every factor and its attribute from operator's perspective is listed in Table 9. 1 whereas a complete description about each factor and the contributing attributes is delivered in *Appendix B*.

Different from the operators' opinion about the PIFs importance, the result of the questionnaires given to the managers demonstrates a quite significant difference. The orange bars in Figure 9. 3 show that the managers consider the technical aspects as the most important and most influencing attributes during supervisory control. The attributes include "System response & feedback", "Design of operating elements" as well as "Display configuration". Other attributes contributing to alarm system and operator supporting system are considered to be slightly less influencing than the previous ones.

The significant difference between how the operators and the managers view the importance of various factors in influencing the work in control room leads to an important point of discussion. One possible explanation to this difference is that the managers have actually been aware of and have acknowledged the main problems control room operators are facing during their work. They must have searched for the solutions to these problems and have implemented improvements to the control and monitoring system through the introduction of more reliable technology. With the optimization of control system by means of increasing its reliability, the engineers and managers were sure that operators' weaknesses are compensated, workload on operators is significantly reduced and errors by operator can be optimally avoided. What is left now is to making sure that the system and the technology is good maintained so that they are always available in a good condition.

For the operators, although all the technology with higher precision, reliability and better user friendliness are introduced to the control and monitoring system, the most important thing is still their own competence. With every change introduced to the system, some problems are solved; others come along, which can directly have influence on operators. Hence, the basic need to be able to cope with any deviance, either in monitoring process flow, or in adapting with new system and technology, they need to have the knowledge, the ability to understand how the system works, and also to receive adequate training and courses. This leads to the need to always taking operators' opinion into account following every system modification to have the awareness of how operators are very easily influenced by the changes made to the system.

Table 9. 1 Weights elicitation for control room PIFs from operator's side

PIF	Weight	Attribute	Global weight
A. Human-System Interface	*0.093*	A1. Displays configuration	***0.026***
		A2. Design of control/operating elements	***0.025***
		A3. Entry of data & instruction	***0.022***
		A4. System response & feedback	***0.020***
B. Control Room Design	*0.104*	B1. Control room layout & components arrangement	***0.030***
		B2. Accessibility	***0.024***
		B3. Ambience & comfort	***0.023***
		B4. Communicating system	***0.027***
C. Workplace design	*0.100*	C1. Workstation configuration	***0.030***
		C2. Labelling and signage of operating elements	***0.035***
		C3. Layout of panels and displays	***0.035***
D. Job Design	*0.107*	D1. Allocation of work	***0.022***
		D2. Variation of work	***0.017***
		D3. Staffing	***0.035***
		D4. Work scheduling & shifting plan	***0.016***
		D5. Proportion of manual (field) work	***0.017***
E. Operator Competence	*0.187*	E1. Skill & knowledge	***0.061***
		E2. Working experience	***0.051***
		E3. Physical characteristics & fitness	***0.036***
		E4. Training & courses	***0.039***
F. Operator Supporting System	*0.130*	F1. Operating & working procedures	***0.035***
		F2. Emergency safeguard & emergency response procedure	***0.048***
		F3. Integrated/computerized operating procedure	***0.048***
G. Alarm system	*0.177*	G1. Number of alarms	***0.025***
		G2. Alarms prioritization	***0.036***
		G3. Available response time	***0.024***
		G4. Signalling & alarm presentation	***0.022***
		G5. Failures indication features	***0.034***
		G6. Maintenance	***0.035***
H. Line Management	*0.102*	H1. Line of responsibility & supervision	***0.020***
		H2. Communication	***0.028***
		H3. Management of change (MOC)	***0.025***
		H4.. Organisation and safety culture	***0.030***

9.2 Development of PITOPA-Control Room (PITOPA-CR)

After the long discussion about differences between the characteristics of field work and the work in control room, it came to the understanding that in order to analyse control room tasks and to recognize the requirements of control room operators, a technique specifically developed for this purpose is needed. Therefore, in this work PITOPA is enhanced to comprise not only the field/on-site works but also the supervisory control conducted in control rooms. Moreover, the technique will provide additional information to be included in the HF analysis in design process by means of the new approach PITOPA-Design.

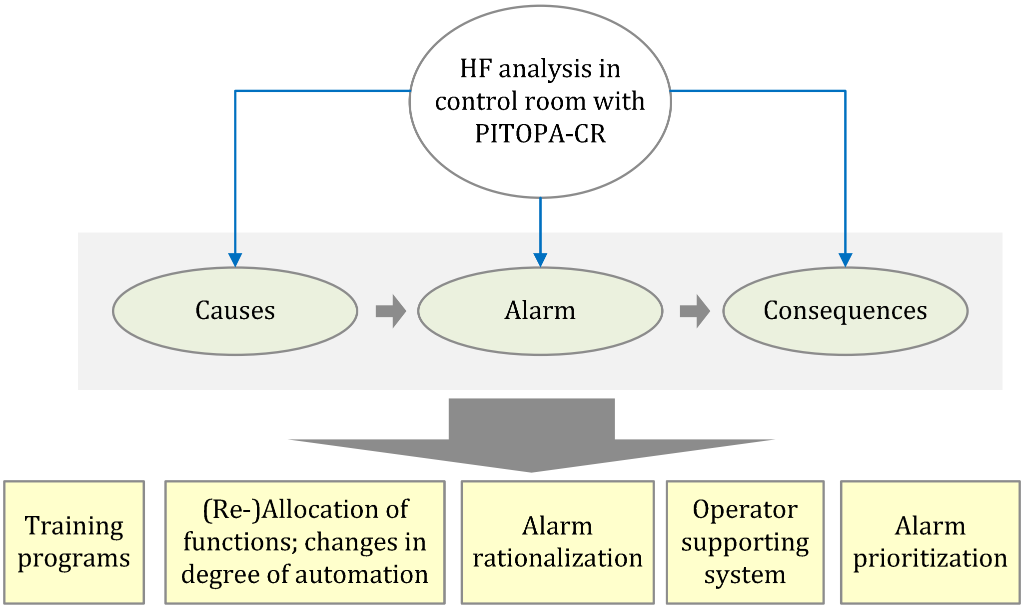

Figure 9. 4 Role of HF analysis in control room in improving alarm management

The new technique for HF analysis in control room developed here will be labelled as “PITOPA-Control Room (CR)” and will provide a way to analyse and recognize system’s deficiencies, both in terms of technical and HF issues. A HF analysis by means of PITOPA-CR delivers the correlation between causes-alarms-consequences, as well as the understanding about how different parts of the system interconnect one with another, and how the system itself interconnects with human beings operating it. These are the basic understandings required to finding the exact solutions to problems in control room and to comprehensively improve the system, which might include an improvement on training programs, the allocation of functions, alarm rationalization, operating supporting system, alarm prioritization and so forth (illustrated in Figure 9. 4).

In Figure 9. 5 the simplified structure of PITOPA-CR is presented. The structure shows the necessary steps in the analysis, which also represents the extent of PITOPA enhancement to cover works in control room. Based on the same consideration about the importance of integrating HF into safety analyses, the new technique for control room must also combine the performance of HAZOPs and HF analysis. The HF part of the analysis itself similarly to PITOPA requires the execution of a task analysis, an operator actions analysis and an evaluation of various PIFs. However, to be applicable for an analysis in control rooms, these 3 techniques need to be modified. Eventually, results coming from the analysis will enable the recognition of various HF issues and problems in performing supervisory control and based on these problems, the exact solutions proposed by different guidelines and industrial best practices can be filtered and accurately utilized.

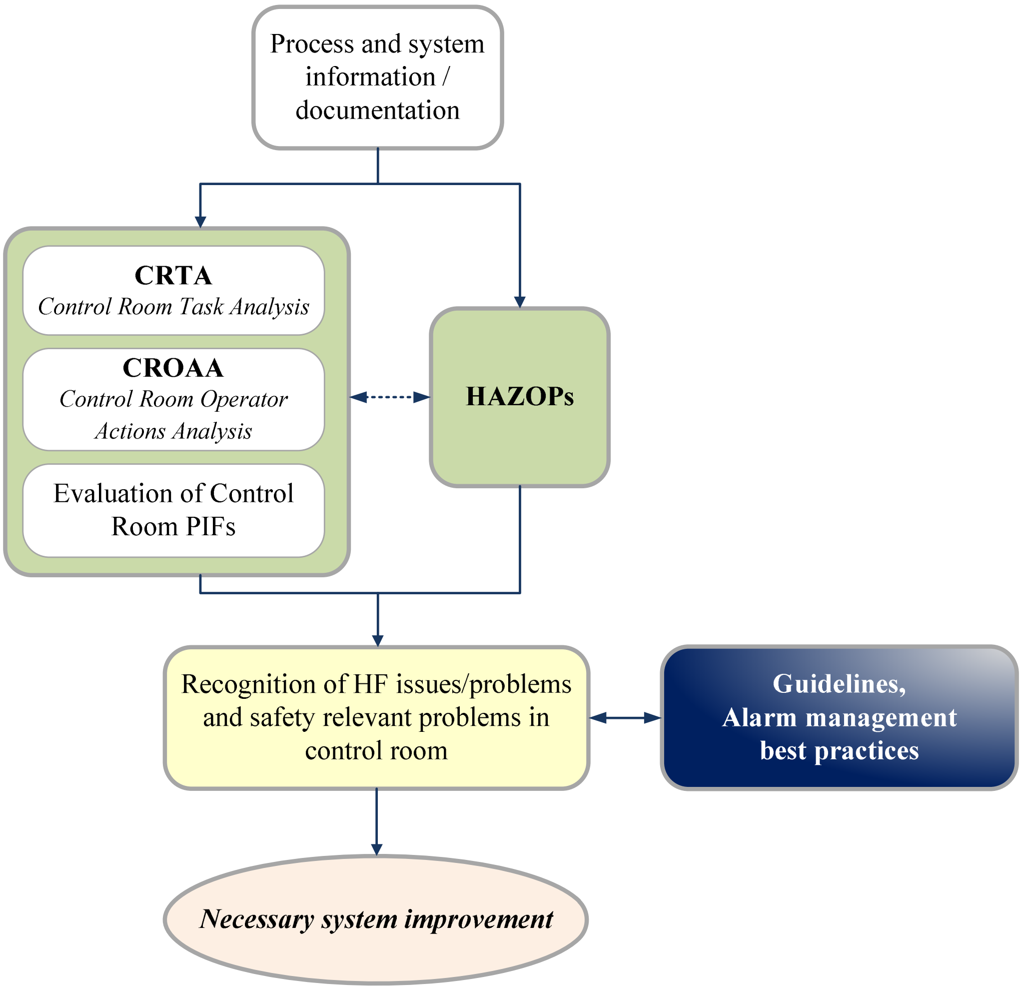

Figure 9. 5 Structure of the new technique for PITOPA-CR

HF analysis by means of PITOPA-CR will focus on two goals, the reduction of alarms triggered by operator's failures during normal work and the avoidance of operator errors during alarm remediation. For this purpose the analysis is divided into two parts; an analysis of normal operation that will aim at the avoidance of operator errors with potentials to causing process deviations and triggering alarms, and an analysis of abnormal operation following an alarm, where operator's contribution is required for remediation. This second part of the analysis holds the key in keeping the process within the tolerable operating state and to stay away from the emergency state.

9.2.1 Analysis of Normal Operation

The analysis of control room work in normal operation is demonstrated in Figure 9. 6 below. The analysis can be initiated after a clear definition of the process is attainable. Since in monitoring, operators are normally assigned to deal with more than one part of the process, it is necessary to define the process (and sub-processes) assigned to one operator to be monitored. In the case where more than one operator are assigned with the same responsibility, then these operators are considered to be in one 'team', and correspondingly, the processes and sub-processes monitored by *one team of operators* must be defined.

Following the assignment of processes to every operator, the next step of the analysis is the combination of a task analysis and HAZOPs, which is similar to the previously developed HF technique HAZOPA (see chapter 6). On all critical tasks identified through CRTA, CROAA and CR-PIFs evaluation must be performed.

I. Control room task analysis (CRTA)

In analysing control room tasks, an initial and crucial step would be to identify operators' responsibility during supervisory control and to classify those tasks into routine tasks and actions for alarm remediation. Alarm remediation is one of the main responsibilities of control room operators, which belongs to an abnormal operation state and hence, will be a part of later discussion. The focus of an analysis in normal operation will first be the normal/routine tasks, which can include general parameters monitoring, inputting set-points, documentation/logging of process data and parameters value, etc.

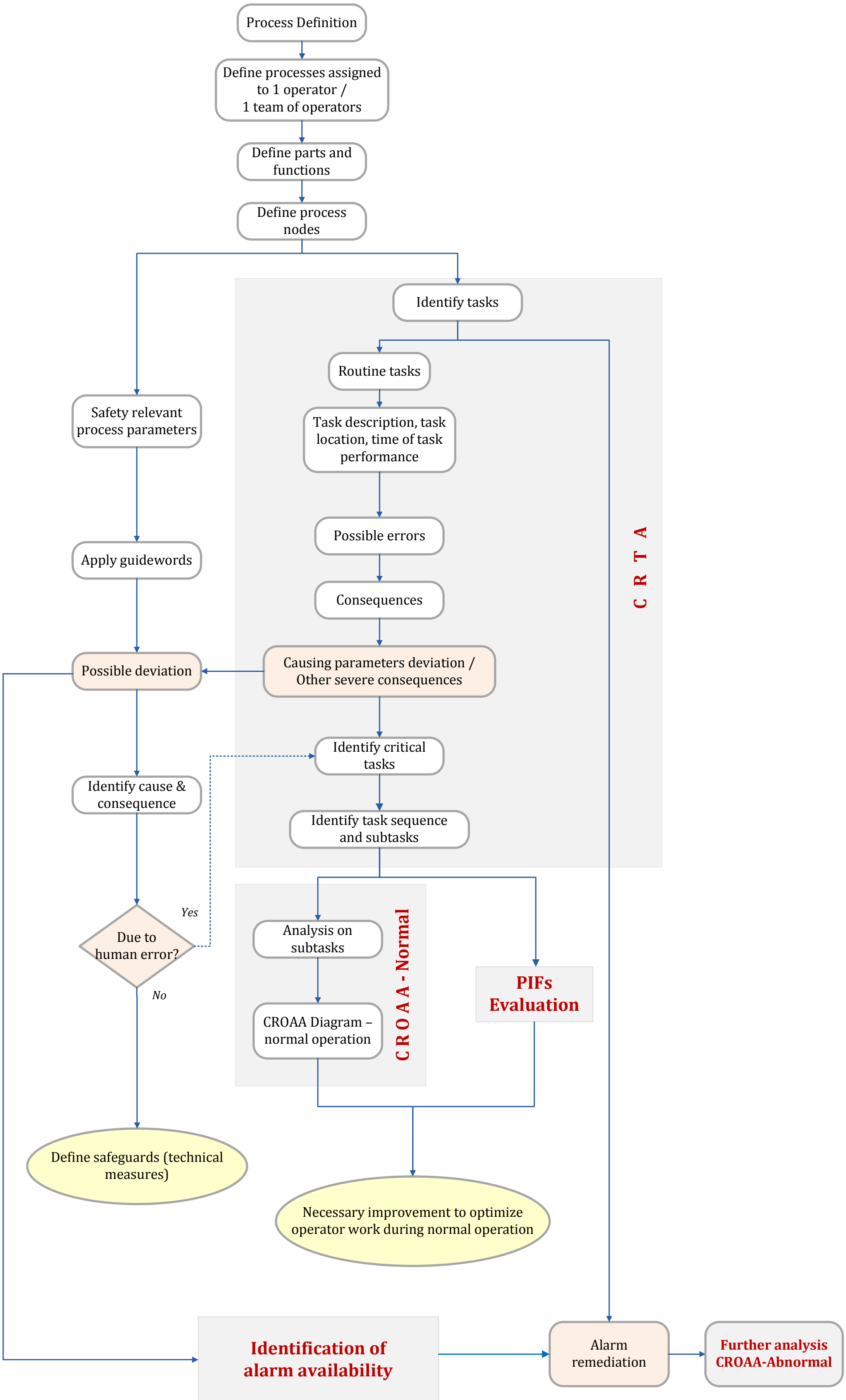

Figure 9. 6 HF analysis for normal operation

The identification of routine tasks in CRTA continues with the identification of possible errors, the consequences of these errors and lastly, the identification of safety critical tasks. These are the tasks, during which an executed error is considered to have high potential to causing significant process disturbances/parameters deviations or other consequences with significant severity that might not directly relate to process disturbances, but can cause negative latent condition, can bring harms to operators or endanger the surrounding environment. For the identification of safety critical tasks, the severity of process deviations and the consequences following errors by operators is evaluated by using a score, qualitatively representing the severity level. Table 9. 2 lists an example set of scores that can be employed for this purpose.

Table 9. 2 Scores representing the severity of error consequences other than causing process disturbance

Score	***Definition***
0	Error can be immediately corrected, necessary safeguards are available to tolerate such errors, and no further dangers or harms can result following this error ***(not safety critical)***
1	Error can be corrected under supervision; some authorizations are needed for correction. If not corrected within the right timing, process will be delayed and dangers might occur ***(safety critical)***
2	Error can lead to an unnoticeable change on process flow, with time can cause serious events and system breakdown ***(safety critical)***

Simultaneous with the performance of CRTA, HAZOPs analysis must as well be conducted. In the case where HAZOPs had been conducted earlier, then the reports to this safety analysis must be kept accessible during CRTA. Only by integrating these two analyses, it will be possible to see the connection between operators misacting in causing process deviations, throughout the whole operation. This means, it will become possible not only to see which possible deviations can occur through which technical failures, but also to see whether those deviations can happen as a result of operator incorrect actions. The worksheet for the simultaneous implementation of CRTA and HAZOPs is provided in Figure 9. 7. To better demonstrate the flow of the analysis, the worksheet shows an example of two processes under supervision of 2 operators (the example is a simple extraction of earlier case-study).

Process assigned to operator (x)	Process Node	Parameters	*Deviation*	Cause	*Due to operator?*	*Corrective actions?*	Safeguards	*Alarms?*
Process 2 (P2): Charging of liquids	N2.1: Liquid charging duct	L2.1: Tank level Liquid A	D1 D2		*Yes*	*Yes*	Level indicator, automatic valve	AL2.1
		L2.2: Tank level Solvent	D3 D4		*Yes*	*Yes*	Level indicator, automatic valve	AL2.2
		L2.3: Tank level stir tank	D5 D6		*Yes*	*Yes*	Level indicator, automatic valve	AL2.3
		Tasks	**Location**	***Possible errors***	***Causing deviation?***	**Severity number**	**Sub-tasks**	
		Task 2.1.1: Flowing liquid & solvent from feedtank	Control room 1st level	Incorrect	D7, D8, D9	*1*	ST 2.1.1.1 ST 2.1.1.2	
		Task 2.1.2: Flow monitoring	Control room 1st level 3rd level	Incorrect	D1/D2, D3/ D4, D5/D6, D10	*0*	ST 2.1.2.1 ST 2.1.2.2 ST 2.1.2.3	
		Task 2.1.3: Level monitoring	Control room 1st level	Incorrect	D1/D2, D3/ D4, D5/D6, D10	*0*	ST 2.1.3.1 ST 2.1.3.2 ST 2.1.3.3	
	Process Node	**Parameters**	***Deviation***	**Cause**	***Due to operator?***	***Corrective actions?***	**Safeguards**	***Alarms?***
Process 4 (P4): Mixing	N4.1: Stir tank	P4.1: Pressure	D7		*Yes*	*Yes*		AP4.1
		T4.1: Temperature	D8		*Yes*	*Yes*		AT4.1
		C4.1: Product composition	D9		*Yes*	*Yes*		-
		L4.1: Tank level	D10		*Yes*	*Yes*	Level indicator, automatic valve	AL2.3
		Tasks	**Location**	***Possible errors***	***Causing deviation?***	**Severity number**	**Sub-tasks**	
		Task 4.1.1: P,T monitoring	Control room	Incorrect	D7, D8, D9	*1*	ST 4.1.1.1 ST 4.1.1.2	
		Task 4.1.2: Level monitoring	Control room 3rd level	Incorrect	D10	*0*	ST 4.1.2.1	
		Task 4.1.3: Sampling	3rd level Laboratory	Incorrect	D9	*2*	ST 4.1.3.1	

Figure 9. 7 Worksheet for HF analysis in normal operation with CRTA and HAZOPs

II. Control room operator actions analysis (CROAA) – normal operation

In dealing with supervisory tasks, operators can easily lose sight of how severe the condition could become following a minor incorrect action. A deeper analysis on errors with significant consequences must be conducted, in order to reveal the underlying problems, and to anticipate the negative outcomes resulting from the error occurrence. For this reason, CRTA cannot stand alone and has to be continued with an analysis of operator actions for control room tasks.

The CROAA (control room operator actions analysis) will scrutinize further the safety critical tasks identified earlier during CRTA and the necessary corrective actions or alarm remediation as summarized in Table 9. 3. During CROAA, the analysis of critical tasks and necessary corrective actions by operators will take place through the generation of CROAA diagrams. However, the analysis of corrective actions and alarm remediation will be a part of CROAA in abnormal operation and will not be discussed here. CROAA diagram for normal operation will first demonstrate the sequence of tasks performance within all sub-processes supervised by one team of operators. Figure 9. 8 demonstrates an example of CROAA-diagram-normal, based on the description of operator tasks listed in CRTA worksheet in Figure 9. 7.

Table 9. 3 Summary of tasks and corrective actions in need of further analysis

Tasks with perceived criticality (analysis in normal operation)		
Task Nr.	**Process Deviation Caused**	**Alarm**
Task 2.1.1	D7, D8, D9	AT4.1, AP4.1
Task 4.1.1	D7, D8, D9	AT4.1, AP4.1
Task 4.1.3	D9	-
Deviations in need of operator actions (analysis in abnormal operation)		
Node	**Deviation**	**Alarm**
N2.1	D1/D2	AL2.1
	D3/D4	AL2.2
	D5/D6	AL2.3
N4.1	D7	AT4.1
	D8	AP4.1
	D9	-
	D10	AL2.3

In reverse to the diagrams of classic OAA, on CROAA diagram (Figure 9. 8) the time sequence to perform operator tasks is demonstrated vertically and the different locations of task performance are depicted horizontally from left to right (Smieszek, 2010). Task locations in this case can be the control room, field or other locations such as the laboratory, supervisor office, warehouse or the logistic office. The presentation of all steps conducted in different locations other than the control room has the purpose to provide better illustration about the whole monitoring activity during operation. This illustration is important since also errors conducted in other locations, such as in field can trigger alarms that might require the operators in control room to cope with the problem. Nevertheless, only the sub-tasks to be done in control room will be analysed deeper in CROAA, whereas the avoidance of errors than can occur during work in other locations are analysed through the classic OAA and/or HAZOPA.

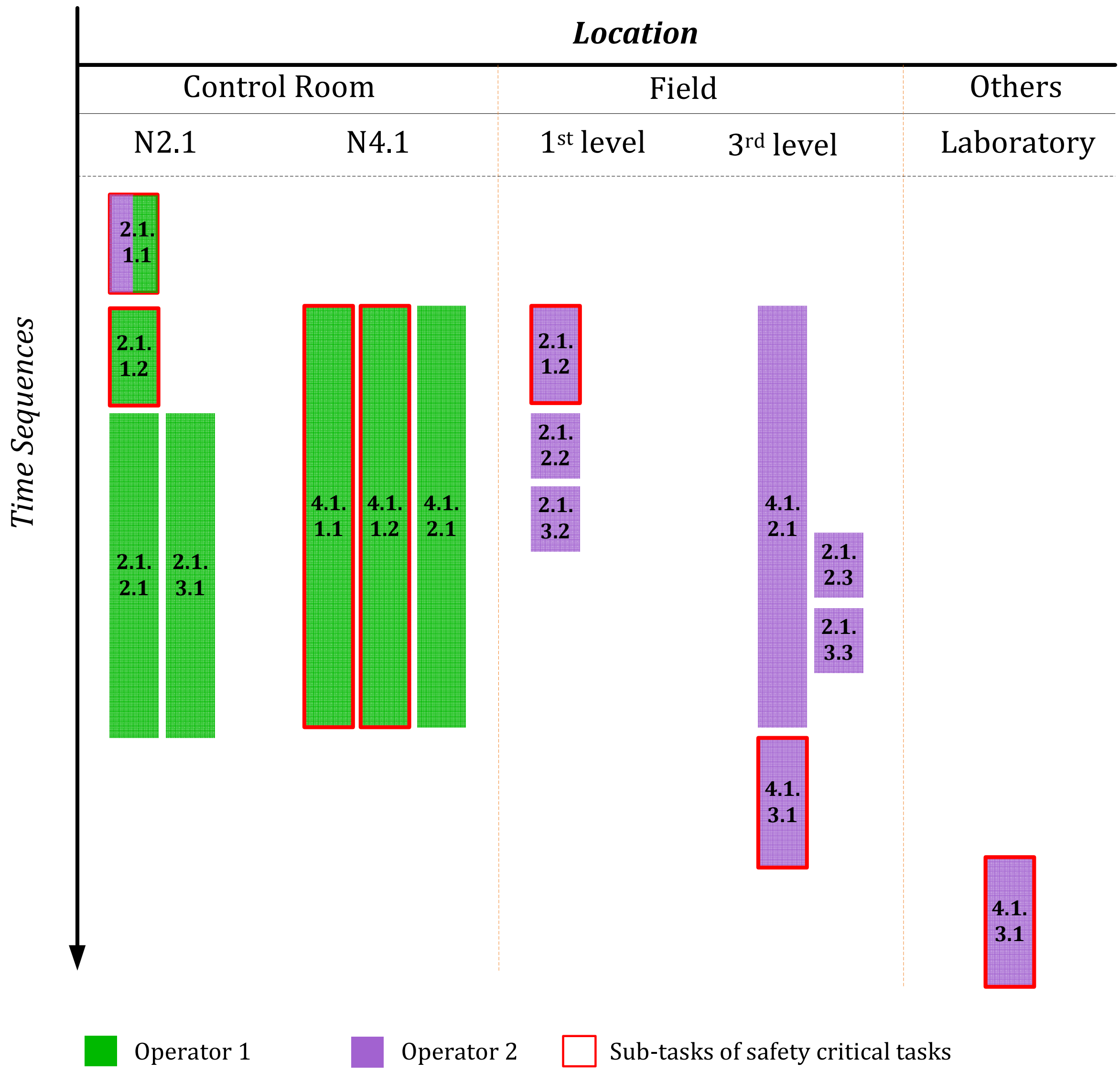

Figure 9. 8 CROAA diagram for normal operation

The sequent steps to be conducted are represented with rectangles in the diagram, coloured differently for every operator. In this example, the green rectangles represent the responsibility of Operator 1 and the purple ones are steps to be conducted by Operator 2. Sub-tasks that might require the contribution of both operators will be marked with both colours. The rectangles outlined with red lines illustrate the subtasks belong to safety critical tasks. In the example Tasks *2.1.1, 4.1.1* and *4.1.3* are identified as safety critical tasks, on the CROAA-diagram-normal all subtasks belong to these critical tasks are outlined with red lines. Further analysis needs to be conducted on these subtasks/steps, since the consequences of any error occurring during these steps can lead to a dangerous event.

CROAA-diagram-normal can help recognizing operator load due to inadequate task sequence and work design, as well as inadequate distance between different locations where operators must conduct actions to complete task sequence. From this diagram, it will also be possible to recognize the need of communication between operators in field and in control room at certain points. Additionally, any work overlapping and overloading that might occur can be identified. However, since these factors are not the only factors that play a big role in affecting operators' performance; an evaluation of all CR-PIFs must be simultaneously performed for every safety critical control room task.

III. Control Room PIFs Evaluation in normal operation

In the beginning of this chapter the importance of an identification of various factors affecting operator's work in control room has already been discussed. Despite the difficulty to model the relevance between influencing factors and operator's working performance related to vigilance, situational awareness, workload and decision making process, evaluating those factors in term of their relevance with task performance and how adequately they are provided to the control room operators can deliver valuable findings. Through such evaluation, relative to each critical task, the factors that can influence operator's work the most and are not necessarily provided to meeting their requirements can be recognized. This will enable the identification of the need to inherently improve the (working) system.

Table 9. 4 Scores for evaluating Control Room (CR) – PIFs

Category	***Score***	***Description***
I	*1*	Factor/attribute has low relevance with task performance; is not affecting operators significantly, however whenever needed is available at sufficient adequacy
II	*3*	Factor/attribute has moderate relevance with task performance; is often needed for completing task and is available at sufficient adequacy
III	*7*	Factor/attribute has high relevance with task performance; is one of the main key factors for task completion and is available at sufficient adequacy
IV	*10*	Factor/attribute has high relevance with task performance; is one of the main key factors for task completion , but is NOT available at sufficient adequacy

For the evaluation of control room PIFs, an evaluation form was developed, which helps in making judgement concerning the relevance level and adequacy of each attribute in supporting operators during performance of certain tasks. Based on the characteristics of different tasks, control room PIFs must be evaluated differently for each critical task. By using the evaluation form in Figure 9. 9 the relevance and adequacy of every attribute subjected to one task is categorized into 4 classes, each of which will be assigned with a score (Table 9. 4), which will be multiplied with the weight of the corresponding attribute as elicited earlier, in order to determine the relative importance of all factors and attributes. Attributes which receive the biggest value of relative importance are determined to be the most influencing PIF attributes.

EVALUATION FORM CR-PIFs – NORMAL OPERATION									
PROCESS:						**Node:**			
Task Nr.: Description:						Number of operators: Task location:			
CR-PIF	Attribute	Category				Score	Weight	Revised score	Relative importance
		I	II	III	IV				
A	A1						*0.026*		
	A2						*0.025*		
	A3						*0.020*		
	A4						*0.022*		
B	B1						*0.030*		
	B2						*0.024*		
	B3						*0.023*		
	B4						*0.027*		
C	C1						*0.030*		
	C2						*0.035*		
	C3						*0.035*		
D	D1						*0.022*		
	D2						*0.017*		
	D3						*0.035*		
	D4						*0.016*		
	D5						*0.017*		
E	E1						*0.061*		
	E2						*0.051*		
	E3						*0.036*		
	E4						*0.039*		
F	F1						*0.035*		
	F2						*0.048*		
	F3						*0.048*		
G	G1						*0.025*		
	G2						*0.036*		
	G3						*0.024*		
	G4						*0.022*		
	G5						*0.034*		
	G6						*0.035*		
H	H1						*0.020*		
	H2						*0.028*		
	H3						*0.025*		
	H4						*0.030*		
							$\Sigma = 1$	Σ	$\Sigma = 1$

Figure 9. 9 Control Room (CR) – PIFs evaluation form for normal operation

The result of CR-PIFs evaluation will lead to the recognition of most necessary system improvements in order to providing human operators with better support, so that the likelihood of errors can be reduced and upset condition due to operator errors during supervisory control can be avoided. With less occurrences of errors by operators that could have caused deviations, the frequency of alarm activation can be reduced, and hence, the likelihood of alarm floods will be reduced.

IV. Identification of alarm availability

The performance of CRTA and HAZOPs enables the recognition of parameter deviations coming from both operator incorrect actions and technical failures. Following parameter deviations, it is important to identify whether alarms are available, to announce the operators of the abnormal process condition. If alarms are available, the next question to be answered is whether any operator response or remediation by operator is required. In the case where operator response is required following an active alarm, the analysis must continue to the second part; an analysis of abnormal operation. If no alarm remediation by operators is required, and the alarms are only activated in order to provide information about the current process status, then an assessment for alarm rationalization must be performed to reconsider whether this announcement must remain as alarms, or they are rather to be classified as warnings. Additionally, availability of necessary safeguards and technical measures to maintain safety of operation following the deviation must be assured.

If in another case, after a parameter deviation occurred no alarm will be activated, it is necessary to make sure whether the availability of alarm is essentially required. Only if after further consideration, it is concluded that no alarms should be activated following the corresponding deviation, then the HF analysis can be terminated at this point and no further analysis for abnormal operation is needed.

9.2.2 Analysis of Abnormal Operation

At the second level, an analysis of abnormal condition of the process will be performed. This analysis will scrutinize deeper the operator actions and responses following an alarm or during process upset following an error. Operator action during abnormal operation holds the most important role in forcing the process back to its normal condition, and if not successfully done, can be a cause of disasters. This is the reason why at this 2nd level analysis the factors influencing operators must be analysed once again in term of their immensity in affecting operator work in control room during upset.

The analysis of abnormal operation is illustrated in Figure 9. 10. Following an active alarm, operators are required to acknowledge and remedy the situation within a certain available time, in order to avoid dangerous state and to bring back the process to the normal operating condition. Any mistake happening during the effort to remedy alarm can have severe consequences. Therefore, every step for alarm remediation must be analysed, in order to identify possible errors during the performance. For this purpose, a control room operator actions analysis (CROAA) for abnormal operation needs to be applied. Additionally, an evaluation of PIFs in abnormal operation is also necessary to be conducted.

The identification of alarms remediation can utilize the assistance of the worksheet in Table 9. 5 below. With this worksheet, the remediation of alarms summarized previously in Table 9. 3 will be identified, as well as other corrective actions required to correct deviations. The corrective measures can be pure technical and fully automated, but can also require operator's contribution. All steps to remedy alarms and all human contribution needed to recover from process upset are analysed in CROAA-Abnormal as discussed in the following section.

Table 9. 5 Worksheet for an analysis of control room work in abnormal operation

Process: **Number of Operators:**		**Alarms**	**Alarm remediation**	**Other necessary corrective measures (manual/automatic)**
Parameter deviation	D1/D2	AL2.1		
	D3/D4	AL2.2		
	D5/D6	AL2.3		
	D7	AT4.1		
	D8	AP4.1		
	D9	-		
	D10	AL2.3		
Operators errors with severe consequence	Error in Task 2.1.1	AT4.1, AP4.1		
	Error in Task 4.1.1	AT4.1, AP4.1		
	Error in Task 4.1.3	-		

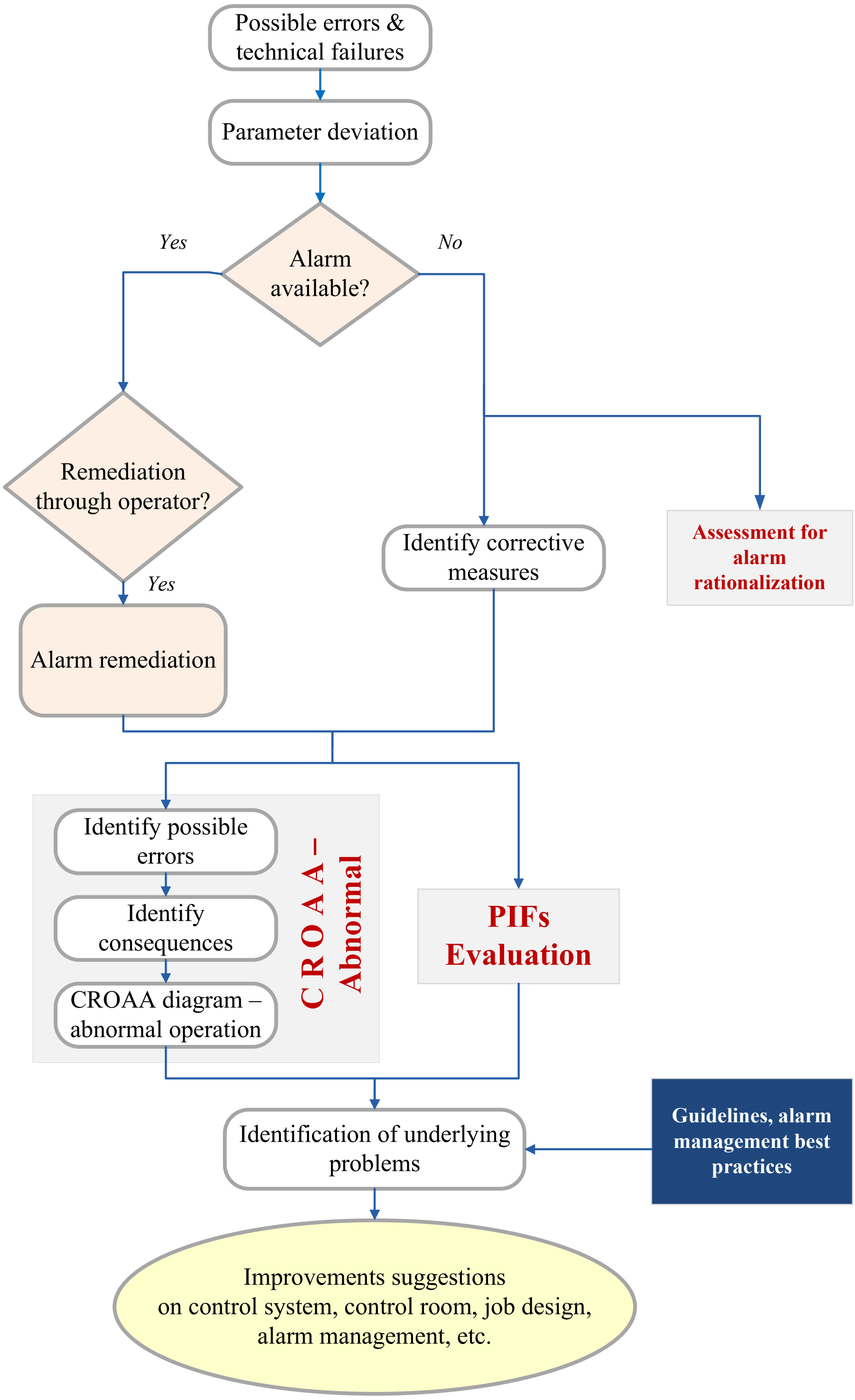

Figure 9. 10 HF analysis for abnormal operation

I. Control room operator actions analysis (CROAA) for abnormal operation

The performance of CROAA-Abnormal is assisted by another worksheet provided in Table 9. 6. The information collected in this worksheet helps to systematically see that in their attempt to recover from upset condition, mistakes can be executed and as a result, the operation can run even farther away from the expected normal condition.

Acknowledging certain intolerable errors during alarm remediation will help in finding crucial points where adequate operator supporting system must be provided to assist operator decision making process. In an extreme case, where the outcome of an error can potentially lead to a disastrous incident, the remediation of certain alarms must exclude operators' contribution, or at the least, alarm remediation can only take place under supervision of the plant manager. Emergency shutdown must as well be accessible as the last system barrier to avoid a disaster from happening.

Table 9. 6 Worksheet for CROAA-Abnormal

<table>
<tr><th colspan="6">Steps for alarm remediation/ corrective actions</th></tr>
<tr><td colspan="2"><u>ALARM: AT4.1</u>
Cause:
D8
Error in Subtask 4.1.1.1</td><th rowspan="2">Possible error</th><th rowspan="2">Consequences</th><th rowspan="2">Further corrective actions</th><th rowspan="2">Emergency shutdown required?</th></tr>
<tr><th>No.</th><th>Description & location</th></tr>
<tr><td>R1.AT4.1</td><td></td><td>ER1</td><td></td><td>CA1</td><td></td></tr>
<tr><td rowspan="3">R2.AT4.1</td><td rowspan="3"></td><td rowspan="2">ER2</td><td rowspan="2"></td><td>CA2</td><td></td></tr>
<tr><td>CA3</td><td></td></tr>
<tr><td>ER3</td><td></td><td>CA4</td><td></td></tr>
<tr><td>R3.AT4.1</td><td></td><td>ER4</td><td></td><td>CA5</td><td></td></tr>
<tr><td rowspan="2">R4.AT4.1</td><td rowspan="2"></td><td>ER5</td><td></td><td>CA6</td><td></td></tr>
<tr><td>ER6</td><td></td><td>CA7</td><td></td></tr>
</table>

Using information from the worksheet for CROAA-Abnormal, steps for alarm remediation and necessary corrective actions will be demonstrated in CROAA-diagram for upset condition, systematically showing the susceptible points where the system tends to fail in coping with human errors. Figure 9. 11 presents CROAA-diagram-abnormal, which provides an analysis of operator action following the activation of alarm *AT4.1* in previous example. On this diagram, the routine tasks during normal operation are illustrated once again. Moving further to the right side of the diagram, the abnormal condition is depicted, which now becomes the focus of this analysis. If an error happens during the performance of a task or a sub-task, the implication of this error in form of a parameter deviation continued with alarm activation, is systematically demonstrated. Following the alarm, steps for remediation are sequentially illustrated with numbered rectangles. The diagram can be expanded to such an extent, until everyone in the analysis team is convinced that all significant possible errors that might have potential to causing disastrous event are anticipated and that adequate support for operators in coping with process upsets can be guaranteed.

Figure 9. 11 provides a clear demonstration about the relationship between alarms, causes and consequences thereof. In some cases, one error can trigger more than one alarm; this can as well be illustrated in the CROAA-diagram-abnormal. The diagram provides also an observation on how operator response following alarms can fully distract their attention in performing routine tasks. Such distraction can as well be resulting in another parameter deviation that can trigger other alarms. Due to the complex nature of the diagram, further errors that are possible to happen during alarm remediation are not shown on the same diagram.

I. Control Room PIFs Evaluation in abnormal operation

To be able to provide the necessary support for operators, an evaluation of control room PIFs must be conducted for abnormal operation. Even though the earlier evaluation for normal operation has revealed significant operators' requirements in performing critical tasks, during an upset they might require additional supports so that reliable performance can be assured. For this reason, CR-PIFs evaluation must take place to analyse every error-prone step of alarm remediation and corrective actions by operators, for example the step *R2* during remediation of alarm *AT4.1* in the example as demonstrated in CROAA-diagram-abnormal (Figure 9. 11).

The basic principles in conducting the CR-PIFs evaluation for abnormal operation are similar to the evaluation for the normal one; nevertheless, the evaluation is now made related to the characteristics of steps operators have to conduct during alarm remediation. Hence, only the heading of the evaluation form needs to be modified, to explicate for which alarm remediation the CR-PIFs evaluation is carried out. The slightly modified evaluation form is provided in Figure 9. 11.

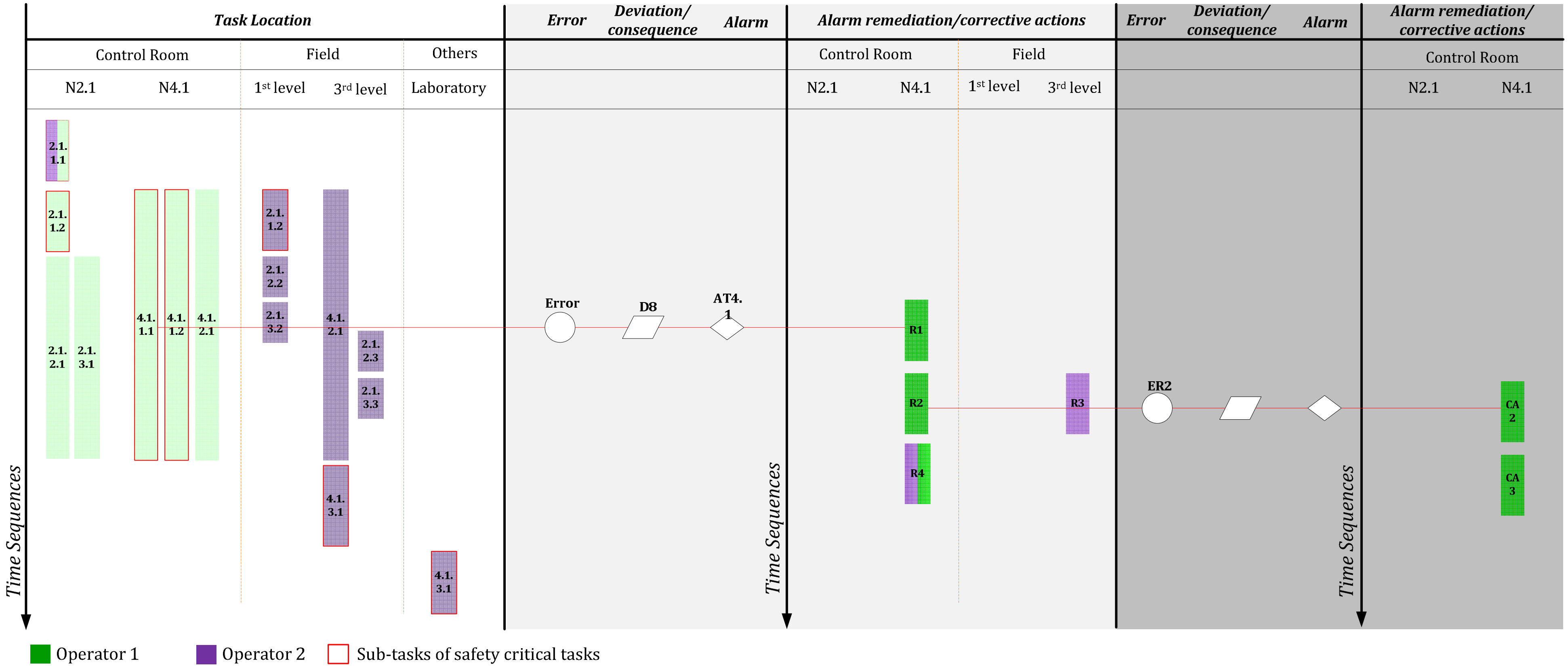

Figure 9. 11 CROAA diagrams of control room work in abnormal operation

<table>
<tr><th colspan="10">EVALUATION FORM CR-PIFs – ABNORMAL OPERATION</th></tr>
<tr><td colspan="7">PROCESS:</td><td colspan="3">Node:</td></tr>
<tr><td colspan="3">Alarm No.:
Remediation step No.:</td><td colspan="4">
Description:</td><td colspan="3">Number of operators:
Location:</td></tr>
<tr><td rowspan="2">CR-PIF</td><td rowspan="2">Attribute</td><td colspan="4">Category</td><td rowspan="2">Score</td><td rowspan="2">Weight</td><td rowspan="2">Revised score</td><td rowspan="2">Relative importance</td></tr>
<tr><td>I</td><td>II</td><td>III</td><td>IV</td></tr>
<tr><td rowspan="4">A</td><td>A1</td><td></td><td></td><td></td><td></td><td></td><td>0.026</td><td></td><td></td></tr>
<tr><td>A2</td><td></td><td></td><td></td><td></td><td></td><td>0.025</td><td></td><td></td></tr>
<tr><td>A3</td><td></td><td></td><td></td><td></td><td></td><td>0.020</td><td></td><td></td></tr>
<tr><td>A4</td><td></td><td></td><td></td><td></td><td></td><td>0.022</td><td></td><td></td></tr>
<tr><td>B, C, D, E, F, G, H</td><td>...</td><td></td><td></td><td></td><td></td><td></td><td>...</td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Σ = 1</td><td>Σ</td><td>Σ = 1</td></tr>
</table>

Figure 9. 12 Extraction of CR-PIFs evaluation form for abnormal operation

9.3 Alarm Prioritization

Several techniques for alarm prioritization were discussed in Chapter 2.6.3, are based on best practices and suggested by reliable guidelines in different industrial branches. However, in this section a technique for alarm prioritization is proposed as an extension of the earlier developed ones, which will take into account the result of the analysis on operator actions in control room.

9.3.1A survey on Alarm Prioritization

Alarm is normally prioritized based on the consequences caused by omission and failure in responding to it. The consequences will have impact on the most important plant criteria that need to be maintained (Rothenberg, 2009), which are:

a. Safety of personnel
b. Environmental impact
c. Product quality, production rate and production plans/schedules
d. Plant and equipment integrity
e. Enterprise finances
f. Company and business reputation

In the scope of the internal industrial survey at Bayer CropScience, a survey was conducted to collect the opinions of plant managers and engineers in viewing how relevant the above criteria are for alarm prioritization. The result of the survey provides relative weights for each prioritization criterion, as listed in Table 9. 7. From the table it can be viewed that the plant managers consider 'safety of personnel' as the most important thing to maintain, and alarm must successfully inform the operators of disturbances that can have impact to this criteria. Moreover, operators must respond correctly to the corresponding alarm, in order to avoid undesired events related to personnel safety.

Table 9. 7 Weights of plant criteria for alarm prioritization

Criteria of alarm impacts	Relative Weight
a. Safety of personnel	*0.32584*
b. Environmental impact	*0.26828*
c. Product quality, production rate and production plans/schedules	*0.10314*
d. Plant and Equipment integrity	*0.10314*
e. Enterprise Finances	*0.07925*
f. Company and business reputation	*0.12035*

9.3.2 Incorporation of CROAA into Alarm Prioritization

Most of the common alarm prioritization techniques suggest combining two considerations; the consequence (and its severity) and the urgency of the corresponding alarm. An alarm will be given a priority of highest level if noticed that a failure to acknowledge this alarm can lead to a severe consequence, and if the operators only have little time to correctly respond to it. In this case, the urgency of alarms is represented by the available time to respond to an alarm. An alarm that announces information related to a severe condition but does not have to be corrected within a narrow time span can be assigned with a lower priority.

However, in viewing the urgency of an alarm, a broader perspective is needed. Urgency is basically the call for immediate attention or the need to perform something immediately or within the shortest possible timeframe. It is true that urgency relates strongly with the amount of available time to conduct certain action, and with less time available, an action is becoming more urgent than usual. But, the need to give immediate attention can also result from the awareness that the consequence by not or incorrectly performing this action can lead to a serious damage, regardless of when this action must be done. Knowing that an undesired outcome can be resulted from an uncompleted action will shift the urgency of such action to a higher level, since an immediate attention to it is now required.

In its relation to alarm prioritization CROAA provides valuable information concerning the necessary operator actions during alarm remediation, about the errors that might occur during these actions and to which consequences those errors can result if not corrected in time. This information relates strongly to the urgency of an alarm, since the understanding about how a severe consequence can be caused by a failure during alarm remediation must be informed to the operator. The operators must be aware of the situation, that in responding to such alarms, higher concentration, discussion among co-workers and supervision from shift leader or plant manager might be needed. Defining urgency from time availability only cannot deliver the most proper priority, since sometimes after a critical alarm is activated, operators have quite much time before the most extreme outcome could occur. However, the urgency of an action rises by knowing that if they wait any longer, the condition will get worse and will become harder to handle.

The necessary operator actions after the activation of alarms are usually not taken into consideration in the common alarm prioritization techniques. Therefore, an extension of those techniques is made in this work. The new technique starts with an evaluation of alarms in terms of their relevance in giving impact or in causing damage to the 6 plant criteria listed in Table 9. 7. This evaluation takes place by giving scores to each alarm, which represents their strength in affecting those criteria if omitted; e.g. using a scale between 0 to 10, where 0 shows no relevance and the score 10 represents the absolute relevance of an alarm to jeopardize certain plant criteria if the operators failed to remedy it. These scores will then be multiplied with the elicited relative weights of each criterion, which will deliver a corrected value of the scores. This will reduce the subjectivity in opinions given during the scoring.

After evaluating how the alarms related to the consequences caused on the 6 plant criteria, it is now important to make a final evaluation by taking the available time as well as the critical characteristics of operator actions to remedy those alarms into account. The evaluation applies the calculation of distance using *k-Nearest-Neighbor (kNN)* Algorithm (see Chapter 2.7.2). The flow of the performance is provided in Figure 9. 13.

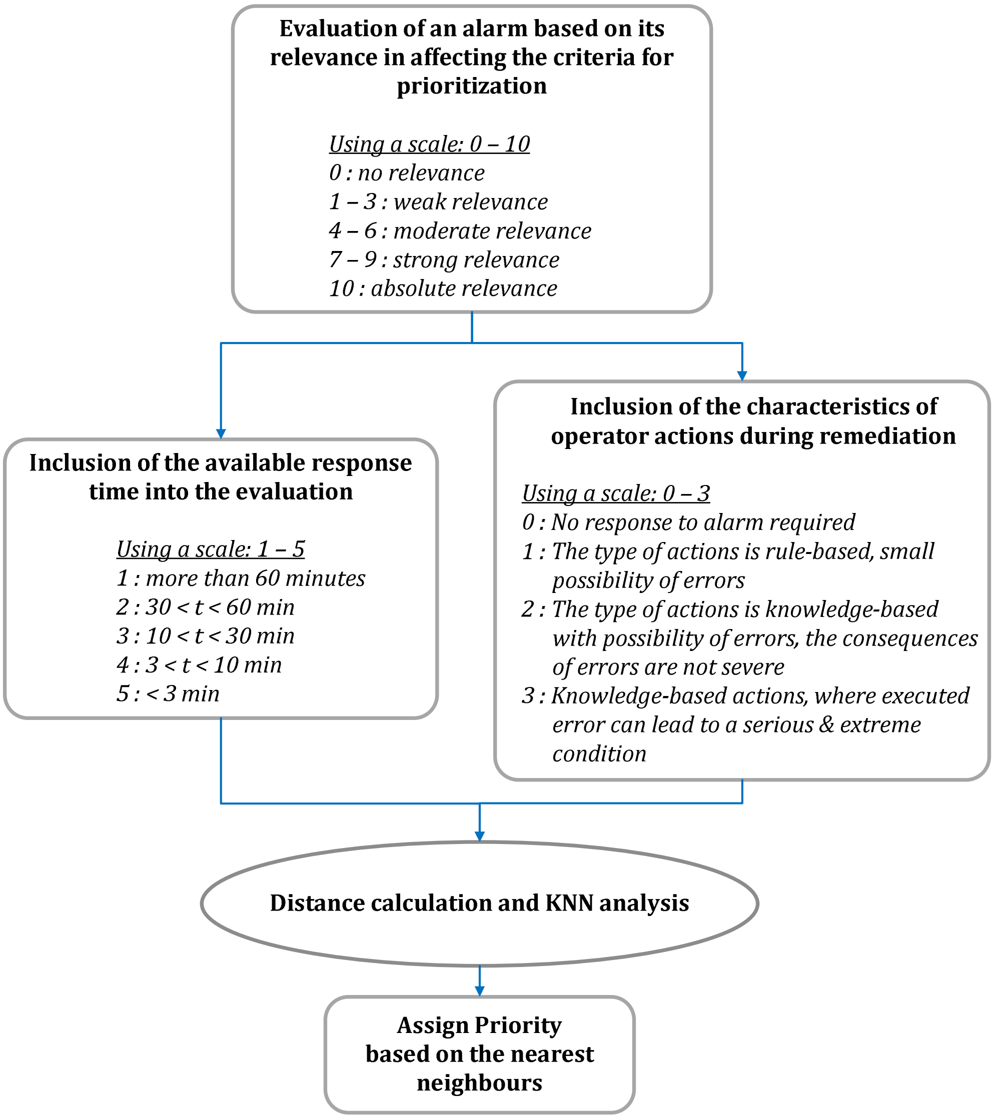

Figure 9. 13 The flow of alarm prioritization by means of the new technique

I. Determination of alarm priority areas for classification purpose

The classification of alarms into 3 priorities is performed based on 3 considerations; how relevant the omission of an alarm in giving impact on the 6 plant criteria is (Priority Factor 1 – *PF1*), how much time is available (*PF2*), and how the characteristics of operator actions during alarm remediation are (*PF3*). Scores as listed previously in Figure 9. 13 will be given to each consideration for every alarm to be prioritized. However, the score for the first consideration (*PF1*), which represents the relationship between alarm omission and the impact caused on the 6 plant criteria, is calculated separately at the beginning. Ultimately for the priorities classification, there will be 3 scores to be taken into consideration, which are the scores for *PF1*, *PF2* and *PF3*.

These 3 final scores are the attributes of the instances and can be assumed as a point *(x,y,z)* in a 3-dimensional coordinate. Since the scales used for judging all three scores are different one from another, for further calculation all scores for *PF1*, *PF2* and *PF3* must be normalized to [0,1] so that all possible combinations of the coordinates *(PF1,PF2,PF3)* will lay between:

$$\mathbf{0 \leq \boldsymbol{PF}1 \leq 1 \wedge 0 \leq \boldsymbol{PF}2 \leq 1 \wedge 0 \leq \boldsymbol{PF}3 \leq 1} \qquad \textbf{Equation 6}$$

To be able to classify the alarms based on their priority within this domain, the boundaries must be set. The priority of a query alarm A_n is to be classified after the rule defined as follows:

$$\boldsymbol{f(PA_n)} = \begin{cases} \boldsymbol{Priority}\ \mathbf{1}, & \mathbf{0.9 \leq PF1 \leq 1 \wedge 0.9 \leq PF2 \leq 1 \wedge 0.9 \leq PF3 \leq 1} \\ \boldsymbol{Priority}\ \mathbf{2}, & \mathbf{0.7 \leq PF1 < 0.9 \wedge 0.7 \leq PF2 < 0.9 \wedge 0.7 \leq PF3 < 0.9} \\ \boldsymbol{Priority}\ \mathbf{3}, & \mathbf{0 \leq PF1 < 0.7 \wedge 0 \leq PF2 < 0.7 \wedge 0 \leq PF3 < 0.7} \\ \underset{\boldsymbol{f(PS)}}{\mathbf{arg\,max}} \left(\sum_{\boldsymbol{i=1}}^{\boldsymbol{k}} \boldsymbol{f(PSi)}\right), & \boldsymbol{else} \end{cases}$$

Equation 7

where $f(PA_n)$ is the priority outcome of the query alarm A_n, n denotes the code used to identify alarms, S_i ... S_k denote the k samples closest to A_n, $f(PS_i)$, i = 1 ... k is known as the priority of a particular k sample (i.e. Priority 1, Priority 2, Priority 3) and i denotes the k-value for classification. Figure 9. 14 below demonstrates the definite areas assigned with 3 different priorities.

After determining the boundaries between each priority area, a classification of the query alarm A_n will be enabled. However, a coordinate can sometimes consist of *PF1*, *PF2* and *PF3* values in different ranges, i.e. *PF1 = 0.8 (lays in the area of Priority 1) , PF2 = 0.5 (area of Priority 2) and PF3 =0.1 (area of Priority 3),* that makes the classification of this point into a certain priority more difficult. The prioritization of such alarm must then be made based on the distance evaluation between the corresponding query alarm and the k-samples whose priorities are known or set.

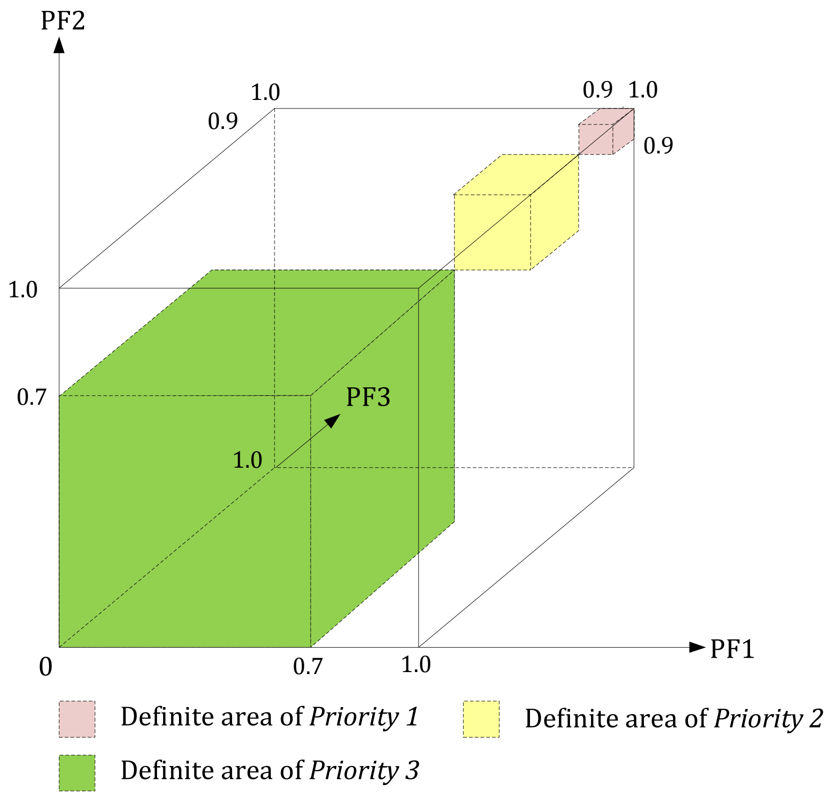

Figure 9. 14 Areas assigned with 3 alarm priorities

kNN algorithm is used to help the classification process. By using a step Δt = 0.05 sample points (k-samples denoted with Si) that represent the definite domains of *Priority 1, Priority 2* and *Priority 3* within $0 \leq PF1 \leq 1 \wedge 0 \leq PF2 \leq 1 \wedge 0 \leq PF3 \leq 1$ can be determined. *kNN* algorithm will measure the distance between the coordinate of the query alarm A_n and these k-samples. Ultimately, the priority of alarm A_n will be classified based on the priority given to the majority of its nearest neighbours (sample points with smallest distance from alarm A_n).

The minimum number of the nearest neighbours to be compared with the query alarm (*k-value*) is arbitrary, an odd number is however more preferable. This technique proposes the *k-value* of 15 to provide an accurate classification, so that for the Equation 2 the value of i is settled to i = 1 … 15.

II. Evaluation of alarms in their relevance in affecting plant criteria

The first step to implementing the new prioritization technique is to evaluate the relevance of the alarm in affecting the 6 criteria by giving a score 0 - 10 to every alarm-criteria relationship. Given an example of a prioritization of 2 alarms, alarm A_{B1} and alarm A_{B2}, the scores that represent the impact of the alarms on the 6 plant criteria is shown in Table 9. 8.

Table 9. 8 Scores showing relevance of a sample alarm (Alarm A) in affecting the 6 plant safety criteria

Criteria	*Relative weight*	*Fixed score Alarm A_{B1}*	*Fixed score Alarm A_{B2}*	*Corrected score A_{B1}*	*Corrected score A_{B2}*
a. Safety of personnel	0.326	3	9	***0.978***	***2.934***
b. Environmental impact	0.268	7	9	***1.876***	***2.412***
c. Product quality, production rate and production plans	0.103	7	10	***0.721***	***1.03***
d. Plant and equipment integrity	0.103	5	9	***0.515***	***0.927***
e. Enterprise finances	0.079	3	10	***0.237***	***0.79***
f. Company and business reputation	0.120	8	8	***0.96***	***0.96***
Total score = *PF1*				***5.287***	***9.053***

The omission of alarm A_{B1} is considered to give only small impact on personnel safety, the equipment integrity and enterprise finances. However, if this alarm was ignored or not successfully corrected, a relative severe impact on the environment and will quality can be caused. Due to these reasons, the company business reputation will be put in danger. Whereby, alarm A_{B2} is very crucial in terms of all 6 plant criteria.

III. Inclusion of both available response time and the characteristics of operator actions during remediation into alarm prioritization

After the impact of omission on the 6 important criteria is evaluated, the inclusion of available time and the characteristics of operator actions into the prioritization must now take place. Table 9. 9 gives the summary of all considerations (represented by *PF1*, *PF2* and *PF*3) to prioritize alarm A_{B1} and A_{B2}. Since the scoring scales used to evaluate each consideration are different, the scores must be normalised first before going to further calculation. The normalisation takes place by means of the following equation:

$$\boldsymbol{x} = \frac{\boldsymbol{r-n}}{\boldsymbol{n_R-n}} \qquad \textbf{Equation 8}$$

where x denotes the normalized score and r = the score given in the evaluation with the corresponding scale [n,n_R].

Table 9. 9 Coordinates of Alarm $\boldsymbol{A_{B1}}$ and $\boldsymbol{A_{B2}}$

Considerations to prioritize alarms	Scores for alarm A_{B1}	Scores for alarm A_{B2}	Normalized scores alarm A_{B1}	Normalized scores alarm A_{B2}
1. ***PF1*** Relevance to plant criteria	***5.287*** (*PF1* in Table 9.8)	***9.053*** (*PF1* in Table 9.8)	***0.5287***	***0.9053***
2. ***PF2*** Available response time	***4***	***5***	***0.75***	***1***
3. ***PF3*** Characteristics of actions during remediation	***1***	***3***	***0.33***	***1***

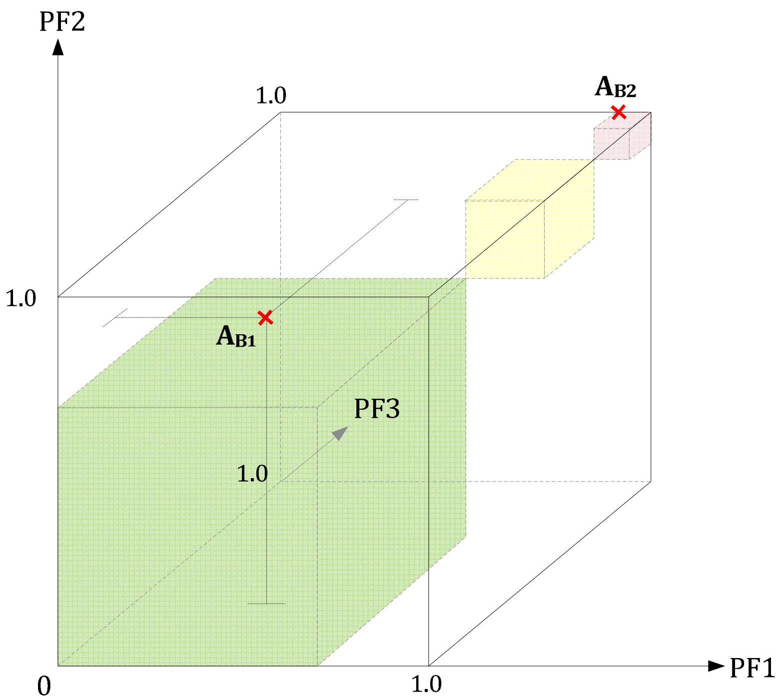

Figure 9. 15 Plot of alarm A_{B1} and A_{B2} on the prioritization domain in 3-dimensional coordinates

By using Equation 8, the normalized scores for alarm A_{B1} and A_{B2} can be calculated, giving the coordinates of both alarms: (0.5287,0.75,0.33) and (0.9053,1,1) respectively as demonstrated in Figure 9. 15 above. For alarm A_{B2} the priority can be easily classified into *Priority 1* (high) according to Equation 6. However, alarm A_{B1} must be prioritised through a classification by means of *kNN* algorithm.

IV. Alarm prioritization with *kNN* algorithm

The *kNN* algorithm will now calculate the distance between alarm A_{B1} and the previously determined k-samples that represent *Priority1, 2* and *3*. The calculation of distance takes place using Euclidean distance. Afterwards, the 15 k-samples that are located nearest to Alarm A_{B1} will be identified, these are namely the nearest neighbours of alarm A_{B1}. The priorities applied to these nearest 15 neighbouring points will be identified, and the priority that is assigned to the majority of those 15 neighbours will be given to alarm A_{B1} correspondingly.

Table 9. 10 kNN result showing the 15 nearest neighbours of alarm $\boldsymbol{A_{B1}}$

Rank	**Distance to alarm $\boldsymbol{A_{B1}}$** (0.5287,0.75,0.33)	**Priority of k-sample** $f(PSi), i = 1 \dots 15$
1	0.104181	3
2	0.105942	3
3	0.106554	3
4	0.108276	3
5	0.12391	3
6	0.124433	3
7	0.125394	3
8	0.126427	3
9	0.128816	3
10	0.129822	3
11	0.130743	3
12	0.131239	3
13	0.141364	3
14	0.145237	3
15	0.146573	3

Table 9. 10 provides the nearest 15 neighbours of alarm A_{B1} and the priorities they are representing. From the result of this calculation, all 15 points nearest to alarm A_{B1} lay in the area of *Priority 3.* A strong assumption that alarm A_{B1} lays in the same area can be taken and hence, this alarm will be assigned with *Priority 3* correspondingly. Mathematically it can be expressed as:

$$\boldsymbol{f(PA_{B1}) = \underset{f(PS)}{\arg\max}\left(\sum_{i=1}^{15} f(PSi)\right) = Priority\ 3} \qquad \textbf{Equation 9}$$

9.4 Intermediate Summary

The new method PITOPA-Control Room (CR) provides a way to analyse operators' responsibility in performing supervisory control and process monitoring. The analysis by means of the new method will lead to the recognition of various HF issues both during normal and upsets condition, which will enable the identification of the most influencing factors that can negatively affect operators' performance in both operating conditions. Identifying these factors can give direction in improving the system and control room configuration to meet operators' requirement and to understand their limitation. The analysis for abnormal condition will deliver specific information about the available alarm system in terms of their adequacy in announcing upsets to the operators and its prioritization concept. By means of this analysis, the common alarm problems such as alarm flooding and false alarms can be avoided and their occurrences will be reduced consequently.

The implementation of PITOPA-CR is summarized in a simplified diagram in Figure 9. 16, which addresses the need to incorporate results coming from the analysis into alarm management programs. In the next chapter, the role of PITOPA-CR in optimizing the life-cycle of an alarm management is delivered in brief.

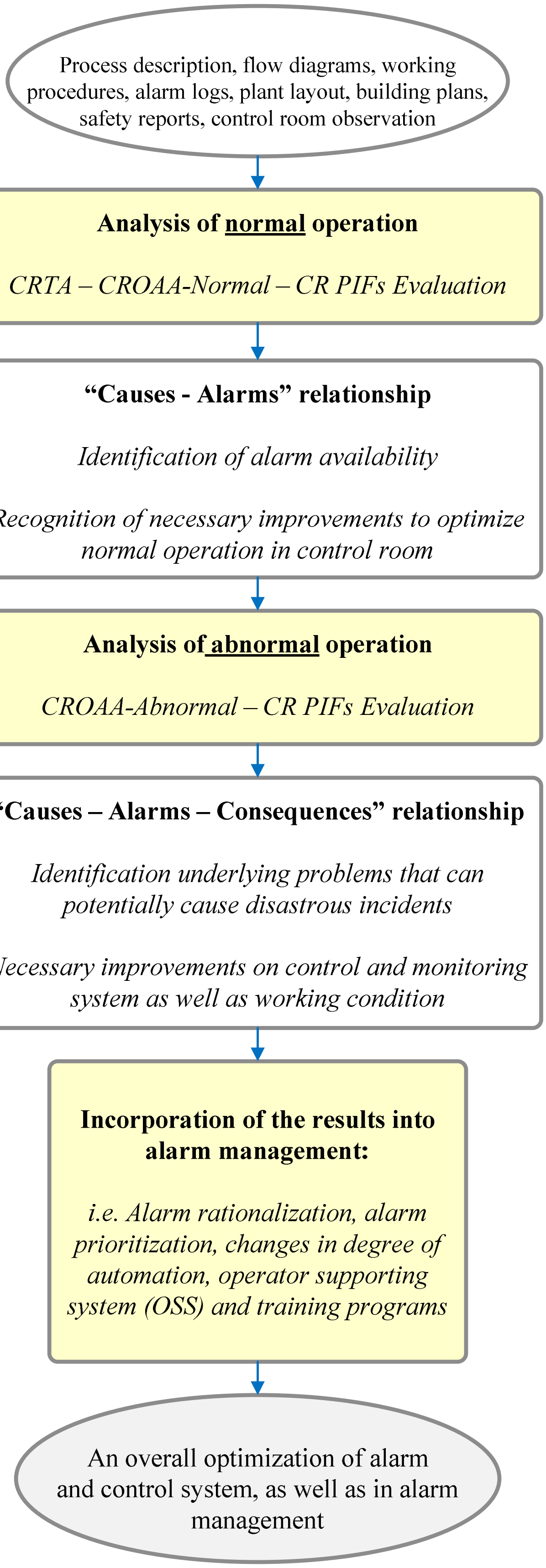

Figure 9. 16 Implementation of PITOPA-CR

CHAPTER 10

INCORPORATION OF OPERATOR ACTIONS ANALYSIS INTO ALARM MANAGEMENT

The new technique for HF analysis in control room described in the previous chapter is a way to incorporate the analysis of operator actions into the whole alarm management activity and lifecycle. The performance of CRTA (control room task analysis), CROAA (control room operator actions analysis) and the evaluation of control room PIFs in both normal and abnormal plant conditions will provide a systematic identification of "causes – alarms – consequences" relationships. Through the understanding about what causes an alarm to go off and to what consequences the omission of the alarm can lead to, an alarm system can be optimally managed. Trough CROAA, operators' contribution in causing deviations that activate alarms can be identified, whereas the evaluation of control room PIFs subsequently will lead to the revelation of the most influencing factors that can force people to perform incorrect actions.

The inclusion of operator actions analysis during process upsets into alarm prioritization was also explained and discussed in detail. However, alarm prioritization is not the only stage of alarm management lifecycle (Figure 2. 9), where operator actions must be taken into consideration. The identified "causes – alarms – consequences" relationships can help a company's alarm management systems in a wider continuum as illustrated previously in Figure 9. 4. The incorporation of the new technique for HF analysis in control room into the lifecycle of alarm management is illustrated in the following Figure 10. 1.

1. *Identification of necessary alarms*

Performance of CRTA and CROAA-normal leads to the identification of process deviations in need of alarms. From this result, it will be possible to re-check, whether those necessary alarms are available and acknowledgeable by operators.

2. Alarm rationalization

On the other hand, the results of CRTA and CROAA-normal also lead to the identification of unnecessary alarms, or warnings that are to be treated differently from alarms. With this information, (re-)rationalizing of alarms will be assisted, and the number of irrelevant alarms or unnecessary warnings can be reduced.

3. Prioritization

In addition to alarm rationalization, results coming from CROAA, particularly from CROOA-abnormal can add valuable information to prioritize alarms. The understanding about the characteristics of operator actions needs to be performed during upsets is necessary to classify the priority of an alarm.

4. Training plans and programs

The results delivered by CROAA in form of normal and abnormal diagrams will help identifying unnecessary alarms so that alarm rationalization is provided with better assistance. Additionally, from the CROAA diagrams, necessary operator actions to remedy alarms and the most probable errors during the corresponding alarm remediation will be identified and anticipated. This information is very essential to be taken into consideration in planning and optimizing operator training programs in working with the alarm system.

5. Design of operator supporting systems and other relevant aspects

Additionally, the evaluation of control room PIFs will provide valuable information to designing an alarm system. The recognition of the most influencing factors during normal tasks and during alarm remediation will provide the design team with the knowledge concerning operator's needs and requirements in performing their work. Consequently, the most necessary design requirements can be correspondingly realized, as to understand operator's limitation and to avoid them from performing incorrect actions that have the potential to causing disastrous events.

6. Optimizing operation

With all information obtained from PITOPA-CR alarm system and alarm management can be improved and optimized, as well as the control system, with which the operators have to work. This will of course lead to an optimization of process operation generally. Moreover, since disturbances and necessary operator actions are anticipated, working procedures can be refined.

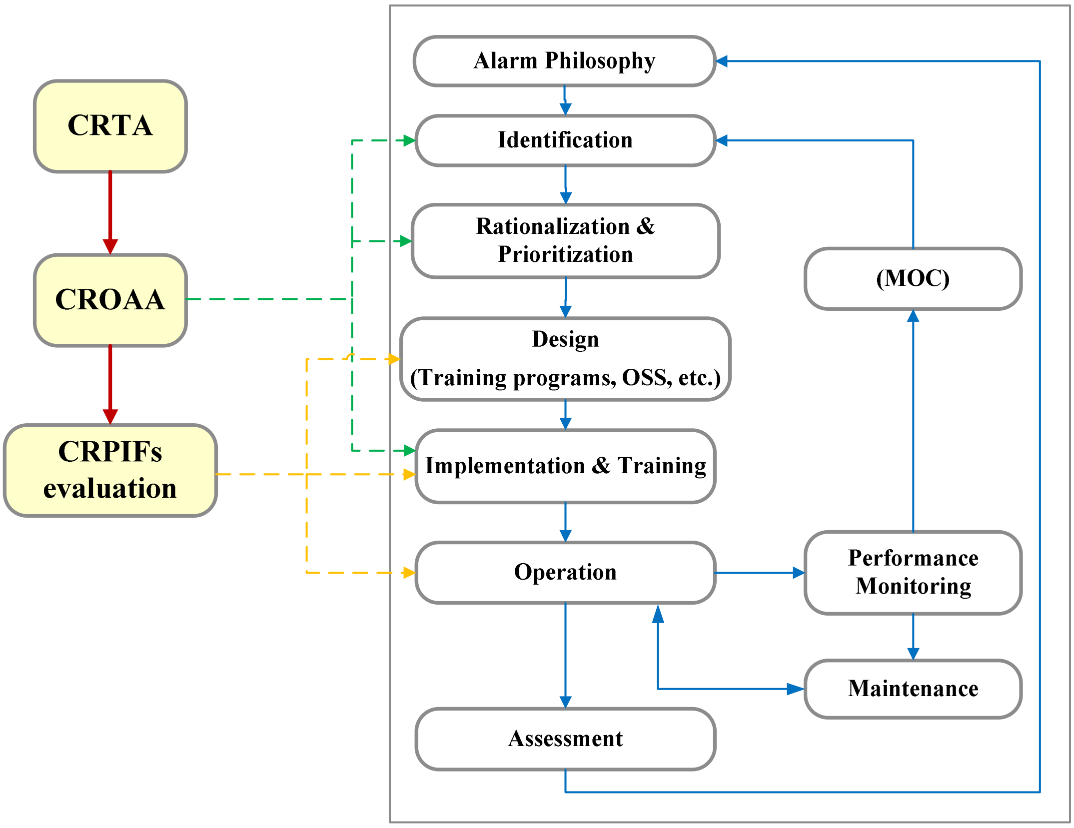

Figure 10. 1 Incorporation of operator actions analysis into alarm management

The performance of both CROAA and control room PIFs evaluation for normal and abnormal operations will on one hand enable the avoidance of operator error that can trigger alarms, which will reduce the potential of alarm floods. On the other hand, these techniques enable the anticipation and prevention of further possible errors during alarm remediation, which will consequently prevent the severe consequences as an outcome of those errors. Incorporating the performance of these new HF techniques into alarm management and into the implementation of the new HF method for design phase developed in this work will provide a way to optimizing plant and process design both from the technical and Human Factors requirements. As a result, an inherently safer plant design that grants operator safety and optimizes production efficiency will be achievable.

CHAPTER 11

RESULTS AND FUTURE WORKS

11. 1 Results

Due to several limitations, the earlier developed method, Process Industry Tool for Operator Actions Analysis (PITOPA) is unsuitable for HF analysis of a plant under design. Hence, PITOPA was enhanced into PITOPA-Design to comprise an analysis of HF condition during the whole phase of process plant design, beginning with the conceptual design until detail engineering in relation with safety analyses conducted during these stages, e.g. HAZOPs. This way, the process plant can be designed not only to meeting engineering and technical requirements, but to as well take into consideration human operators' requirements in term of their safety and working efficiency. Combined with the application of classic PITOPA during commissioning phase and plant operation, both methods PITOPA-Design and the classic PITOPA will provide a systematic way to consider, analyse and recognize problems in plant design that can significantly affect operators' performance, so that safeguards, safety equipment, working procedures or trainings for operators can be anticipated and planned correspondingly.

The new method PITOPA-Design does not address in particular the design of control room and control system, or any other aspects that specifically relate with operators work during supervisory control. However, PITOPA-Design directs the users to separately analyse operators' requirements in performing supervisory tasks and afterwards, to make improvements or design suggestions corresponding to the analysis results. For this purpose, once again a modification was made on the classic PITOPA, in order to provide a way for HF analysis in control room work, which has led to the development of PITOPA-Control Room (PITOPA-CR). With similar logic, PITOPA-CR scrutinizes every condition related with operator performance in working with the control system, to acknowledge active alarms and to cope with upsets. PITOPA-CR delivers results that can be exploited to improve alarm management system, among others through a better alarm rationalization and prioritization. For these reasons, a new technique for alarm prioritization was additionally developed to enable the proper utilization of PITOPA-CR result in the prioritization of alarms. This new technique

PITOPA-CR can be implemented in existing plants, and can as well be interconnected with PITOPA-Design, in particular during late basic until detail engineering, where control system and control rooms are being configured.

The whole work described in this report provides a systematic way to incorporate Human Factors (HF) into design and operation of process plants, for operators' work both in field and in control room as demonstrated in Figure 11. 1. A proper implementation of PITOPA-Design and a frequent HF audits by means of the classic PITOPA, both in a combination with PITOPA-CR will extensively optimize process and occupational safety, increase process efficiency and productivity and less but never the least, will radically reduce unplanned costs.

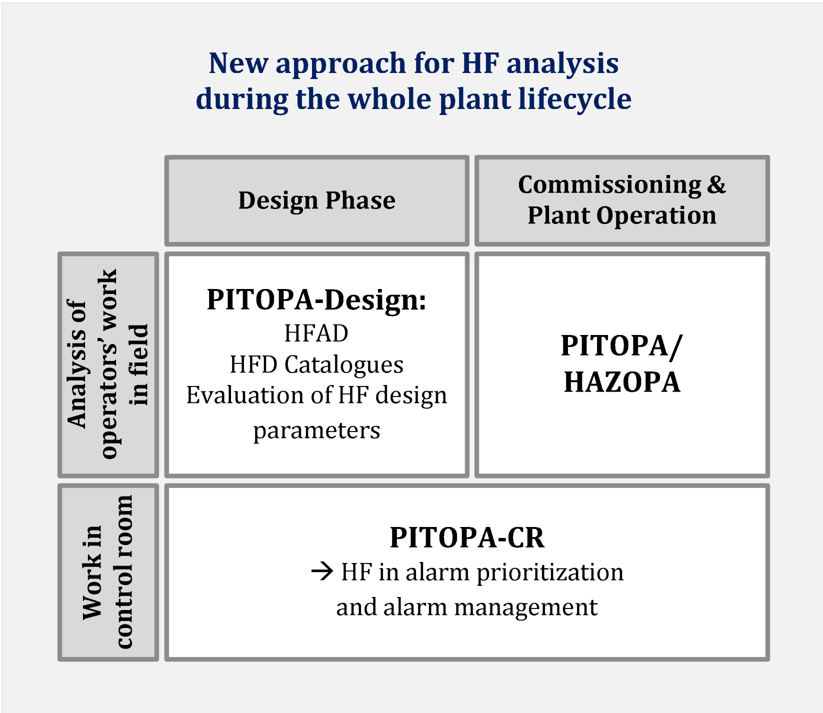

Figure 11. 1 Area of application of the new approach for HF analysis during plant lifecycle

The work has achieved the desired results; however, several recommendations for future works are suggested in the following section.

11. 2 Future Works

The method and techniques developed in this work attempt to provide a clear systematic in performing HF analysis; either it is conducted during design, commissioning, or operation of a process plant. This systematic can however be very confusing, and the amount of information collected and resulted from the analysis can become enormous with the increasing complexity of the plant. Performing a paper-based analysis is for that reason not recommended. Therefore, there is an inevitable need to computerize the techniques in order to ease the implementation, and most importantly, to maintain a reliable analysis since the correct flow of the analysis is assured.

Further recommendations will be made more in the area of PITOPA-CR. For the development of this technique, factors influencing human operators during supervisory control were re-identified and broken down into smaller attributes to one extent where a hierarchy was obtained. The author still senses the need to explore the factors that can influence human beings during control room work, and to afterwards form the proper hierarchy correspondingly. Additionally, the author recommends the identification of PIFs that are most relevant to operators' action during abnormal operations or upsets. Several factors can have bigger impact on operators during plant upsets than in normal operation generally. Hence, the PIFs for works during normal and abnormal conditions need to be differently identified.

Moreover, the need to explore other techniques for evaluating these influencing factors rather than using AHP is considered to be of great importance. AHP used in this development relies too much on operators' subjective opinions and feelings. Such subjective feelings can vary more widely if used in judging work load in term of stress level, information processing and vigilance rather than when used to evaluate physical load.

Related to the whole development, further validations of PITOPA-Design, HAZOPA, PITOPA-CR and the technique for alarm prioritization in process industries are necessary to be conducted. Focusing to alarm prioritization, validations and more industrial observations are needed to refine the determination of areas/domains for alarm prioritization that is used for classifying alarm priorities. Either a change of boundaries need to be performed can only be answered after thorough field analysis and deeper discussion with practitioners.

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APPENDIX A

Questionnaire for HF-Design Evaluation in Detail Engineering

Technical Facilities				
1	**Equipment General Condition**			*Total score / 2*
1.1	Technical system Is sufficient time available for task performance?	☐	Yes	2
		☐	No	1
	Technical system condition:	☐	Normal	1
		☐	Abnormal	1
		☐	Emergency	4
	Operability:	☐	Easy to operate	1
		☐	Difficult/confusing	4
1.2	Process safety condition Is the part to be operated safety relevant?	☐	Yes	5
		☐	No	1
	Is necessary safety equipment available?	☐	Yes	1
		☐	No	5
		☐	Not safety relevant	0
2	**Human-System Interface**			*Total score / 3*
2.1	Display Is display provided to the operators?	☐	Yes	1
		☐	No	5
	If yes: Appearance adequacy:			
	Adequate colorings:	☐	Yes	1
		☐	No	2
	Suitable amount of information displayed:	☐	Yes	1
		☐	No	2
	Readible information:	☐	Yes	1
		☐	No	2
	If no: Is it necessary for process monitoring?	☐	Yes	5
		☐	No	1
	Is up-dating for displays included in the MOC?	☐	Yes	1
		☐	No	3
2.2	Communication System Adequate communication system to support communication between field an control room:			
		☐	Available	1
		☐	Not available	5
		☐	Not necessary	0
	Adequate system to support communication between different locations in field:			
		☐	Available	1
		☐	Not available	5
		☐	Not necessary	0
2.3	Feedback and alarms Feedback to operators to confirm task completion?	☐	Available	1
		☐	Not available	4
		☐	Not necessary	0
	Emergency alarms adeuqately located?	☐	Yes	1
		☐	No	3
	Simultaneous and false alarms excluded?	☐	Yes	1
		☐	No	3

3	Environmental Factors			*Total score / 5*
	For tasks conducted outdoor:			
3.1	Illumination			
	Adequate lighting available?	☐	Yes	1
		☐	No	5
		☐	Not necessary	0
	Glare and reflections excluded?	☐	Yes	1
		☐	No	5
3.2	Temperature, humidity and wind			
	Suitbale working apparel & clothing for the corresponding temperature available?			
		☐	Yes	2
		☐	No	10
		☐	Not necessary	0
3.3	Noise			
	Noise reduction system / ear protection available for operators?			
		☐	Yes	2
		☐	No	10
		☐	Not necessary	0
3.4	Vibration			
	Vibration reduction system available?	☐	Yes	2
		☐	No	10
		☐	Not necessary	0
3.5	Air quality and toxicity			
	Toxic atmosphere avoided?	☐	Yes	2
		☐	No	10
		☐	Not relevant	0
	For tasks conducted indoor:			
3.1	Illumination			
	Adequate lighting available?	☐	Yes	1
		☐	No	5
		☐	Not necessary	0
	Glare and reflections excluded?	☐	Yes	1
		☐	No	5
3.2	Temperature, humidity and wind			
	The temperature of working area:			
		☐	Cool (< 21°C)	3
		☐	Normal (21 - 33°C)	1
		☐	Hot (> 33°C)	5
	Operators are to work near heated process equipment?			
		☐	Yes	5
		☐	No	1
3.3	Noise			
	Noise reduction system / ear protection available for operators?			
		☐	Yes	2
		☐	No	10
		☐	Not necessary	0
3.4	Vibration			
	Vibration reduction system available?	☐	Yes	2
		☐	No	10
		☐	Not necessary	0
3.5	Air quality and toxicity			
	Toxic atmosphere avoided?	☐	Yes	1
		☐	No	4
		☐	Not relevant	0
	Adequate ventilation:	☐	Available	1
		☐	Not available	3
		☐	Not relevant	0
	Air conditioning/purifying system:	☐	Available	1
		☐	Not available	3
		☐	Not relevant	0

4	**Workplace Design**		*Total score / 2*
4.1	Layout		
	Adequate space available for task performance?	☐ Yes	1
		☐ No	3
	Consistent arrangement of equipment to avoid confusion:		
		☐ Yes	1
		☐ No	2
		☐ Not relevant	0
	Equipment arrangement allows movement?	☐ Yes	1
		☐ No	2
		☐ Not relevant	0
	Arrangement allows avoidance of direct contact with heated equipments?		
		☐ Yes	1
		☐ No	3
		☐ Not relevant	0
4.2	Accessibility		
	Necessary equipment/tools/parts are physically reachable during task performance:		
		☐ Yes	1
		☐ No	2
		☐ Not relevant	0
	Stairs, ladders and ramps are adequately placed:	☐ Yes	1
		☐ No	2
	Adequate pathways to connect different process parts available for task performance:		
		☐ Yes	1
		☐ No	4
		☐ Not relevant	0
	Pathways lead the shortest way to reach a different task location:		
		☐ Yes	1
		☐ No	2
		☐ Not relevant	0
Human			
1	**Skill & Knowledge**		*Total score / 2*
1.1	Type of task		
	Task type	☐ Skill-based	2
		☐ Rule-based	4
		☐ Knowledge-based	6
	Individual task?	☐ Yes	2
		☐ No	4
1.2	Qualification and Experience		
	Operator has the required skill and knowledge?	☐ Yes	1
		☐ No	2
	Operator has the required experience?	☐ Yes	1
		☐ No	2
	Has operator completed manadatoty trainings related to task perforamance?		
		☐ Yes	1
		☐ No	3
		☐ Not necessary	0
	Restrictions for people with certain age or behaviour considered?		
		☐ Yes	1
		☐ No	3
		☐ Not necessary	0

2	**Manual & Physical Handling**			*Total score / 2*
2.1	Physical Load			
	Any manual handlings of materials or equipment necessary?	☐	Yes	3
		☐	No	1
	Reduction of pullling, pushing, carrying, lifting and lowering possible?	☐	Yes	1
		☐	No	3
		☐	Not necessary	0
	Physical hard task?	☐	Yes	4
		☐	No	1
2.2	Additional Tools & Safety Equipment			
	Necessary additional tools available?	☐	Yes	1
		☐	No	3
		☐	Not necessary	0
	Are additional tools easy to operate?	☐	Yes	1
		☐	No	2
		☐	Not necessary	0
	Is necessary protective clothing provided?	☐	Yes	1
		☐	No	3
		☐	Not necessary	0
	Performance reduction caused by the wear of protective clothing avoided?	☐	Yes	2
		☐	No	1
		☐	Not necessary	0
3	**Stress Level**			*Total score / 3*
	Adequate support for tasks requiring high concentration available?	☐	Yes	1
		☐	No	3
		☐	Not relevant	0
	Adequate support for tasks with high monotony level and causing boredom available?	☐	Yes	1
		☐	No	3
		☐	Not relevant	0
	Adequate support to ease task performance with high potential of hazardous risk available?	☐	Yes	1
		☐	No	4
		☐	Not relevant	0
Management & Organisational System				
1	**Job Design**			*Total score / 2*
1.1	Task Frequency			
	Shifting plans completed?	☐	Yes	1
		☐	No	4
	Is the goal of task completion clearly determined and explained to operators?	☐	Yes	1
		☐	No	6
1.2	Job Description			
	Are tasks broken down into definite steps and clearly described?	☐	Yes	2
		☐	No	10

2	**Line Management and Procedures**		*Total score / 3*
2.1	Line of Responsibilities		
	Clear hierarchy of responsibility in performing the task?		
		☐ Yes	1
		☐ No	2
	Person responsible in planning and sharing the task assigned?		
		☐ Yes	1
		☐ No	2
	Person responsible in giving instructions during task performance assigned?		
		☐ Yes	1
		☐ No	2
	Person responsible in giving supervision assigned?		
		☐ Yes	1
		☐ No	2
	Person to be informed of task completion clearly assigned?		
		☐ Yes	1
		☐ No	2
2.2	Procedures		
	Means to explain the task to operators available?	☐ Yes	1
		☐ No	2
	Procedural manual/instructions for task performance available?		
		☐ Yes	1
		☐ No	4
	Up-dating plans of manuals and working procedures prepared?		
		☐ Yes	1
		☐ No	4
2.3	Supervision		
	Adequate supervision for task performance available?		
		☐ Yes	1
		☐ No	4
	Supervision from contractors or third party required?		
		☐ Yes	6
		☐ No	1
3	**Task Information**		*Total score / 3*
3.1	Labels & Signs		
	Equipment and process components related to task performance are adequately labelled:		
		☐ Yes	1
		☐ No	4
	Instructions and warnings are readible and noticeable:		
		☐ Yes	1
		☐ No	3
	Up-dating plans for labels and signs are prepared:	☐ Yes	1
		☐ No	3
3.2	Communication		
	Adequate communication between field operators available?		
		☐ Yes	1
		☐ No	3
		☐ Not necessary	0
	Adequate communication between field and control room available?		
		☐ Yes	1
		☐ No	4
		☐ Not necessary	0
	Adequate communication between shifts available?		
		☐ Yes	1
		☐ No	3
		☐ Not necessary	0
3.3	Documentation		
	Adequate system for documenting task completion available?		
		☐ Yes	2
		☐ No	10

APPENDIX B
DESCRIPTION OF CONTROL ROOM PIFS AND THE CONTRIBUTING ATTRIBUTES

A. Human System/Machine Interface (HSI/HMI)

HSI holds the role in assuring a reliable information exchange between the process and the operators, since this interface is the boundary across which process information is transduced by sensors and displayed to the operators (CCPS, 1994). Design of HSI must support the recognition, tolerance and recovery from any possible human errors during process monitoring (O'Hara, et al., 2002). The attributed associated with HSI are configuration of displays, design of control, system response and feedback, and the entry of data and instruction.

A1. Displays configuration

The term ‚displays configuration' in an analysis by means of PITOPA-CR represents the way in which process information is presented to control room operators by a display system. The evaluation of this attribute will comprise necessary design requirements for reliable process monitoring by operators, including:

- Presentation of only necessary and relevant information for operators
- Appropriate display format for particular tasks: suitable use of text, graphs, charts or tables
- Design of displays elements including colouring, use of icons and symbols, abbreviations, scales, arrows and the size of presented information
- Display networks/structure: the use of hierarchical, sequential or relational structure

A2. Design of control

Controls are devices that interconnect human with HSI and consequently with the process. In the context of control room work can include:

- General conventional control devices i.e. pushbutton or rotary control for instance at panels and consoles
- Computer-based input devices i.e. function keys and keyboard, mice, trackballs, joystick, touch-screen, light-pen, graphic tablets or speech input devices.

The evaluation of the attribute ‚design of control should observe whether the appropriate control devices have been selected to providing support for operators in performing the tasks they are assigned with. Additionally, the location of those devices, accuracy, speed and human suitability must be taken into consideration during the evaluation.

A3. Entry of data and instruction

The entry of data and instruction relates with the selected input control device described in point A2. However, this attribute represents more the way in which the operators conduct the whole activity and how the system is designed to prevent accidental input or actuation. Several examples of observation that should be taken in evaluating this attribute are:

- If operators are required to entry process data that will significantly affect the flow of the process, then the system needs to ask for confirmation and must be sensitive enough to any unfeasible inputs.
- If certain parameters must be kept unchanged, then any possible manipulation by operators must be assured to prevent accidental interference.
- If for data entry or for giving instructions the operators need to input long line of numbers or text, then it can be considered to provide them with several options from possible ranges of data. The operators will then have to only choose the desired instruction by for instance clicking on one of those options.

A4. System response and feedback

In relation to the attribute A3, system response and feedback describes the computer's behaviour after receiving information inputted by the operators and its ability to inform the operators that their input has been received or is being processed. Additionally, the time between the submission of the instruction and the presentation of feedback from the computer is essential, since delay in giving confirmation after an entry of data, can mislead operators to a wrong decision, especially if they are required to subsequently input next instructions correspond to the result of the previously conducted step.

B. Control Room Design

Control room is frequently expressed as the workplace where operators conduct all activities at different workstations. Such workplaces or control rooms are hence the facilities that house the workstations and additional equipment that provide the environment where operators conduct their tasks. Attributes contributing to the design of control room that need to be evaluated in PITOPA-CR are control room layout and equipment arrangement, accessibility, ambience and comfort, and communicating system.

B1. Control room layout and equipment arrangement

Since as previously mentioned, control room is consisted of several workstations and equipment, a good arrangement and positioning of those elements need to be maintained in providing support for operators. The evaluation comprises:

- Arrangement/layout of furniture, instruments and other equipment to consistently meet the staffing and task assignments
- Document organisation and storage
- Storage of tools, protective clothing and equipment i.e. helmet, safety gloves, masks, etc.
- Positioning of emergency equipment and exit

B2. Accessibility

Related to point B1, the access to all necessary elements in the control room must be kept available. The layout of control room and the arrangement of different equipment must provide the operators with adequate accessibility in reaching for instance working procedures and emergency exit, within a relative narrow time frame. Additionally, the access to displays and controls required for continuous monitoring needs to be assured in any process condition, for all operators working at that time regardless to the specific tasks assignments. This is to enable any operators working at that moment to gain awareness of process abnormality, even if they were not assigned with the monitoring of the particular part of the process.

Another point evaluation regarding the "accessibility" is the sufficient access between the control room with other necessary locations, such as the plant manager or the supervisor office, room for personal storage (including restrooms, room for eating and lounge facilities), and laboratories. At plants where direct operators involvement in field is required, the shortest and safest access to reach the plant needs to be available.

B3. Environment, ambience & comfort

Working environment in a control room needs to be maintained within the operator's comfort range. Besides the availability of the above mentioned facilities; resting and eating area, restrooms and lounge facility, operator's comfort during working in the control room must be assured by maintaining the thermal comfort, illumination and the auditory environment.

- Thermal comfort includes room temperature, air humidity and adequate ventilation
- Illumination; level of illumination for different activities must be ensured, for instance lighting at workstations and individual controls, for reading and writing area or additional emergency lighting for special condition

- Auditory environment includes the background noise level in the workplace. Noise can come from the busy line of communication between field and control room operators or due to a number of stale alarms that are constantly active.

B4. Communicating system

Communicating system plays an essential role in assuring operation reliability especially at the plants where manual intervention of operators is still required. Such intervention requires certain operators to conduct tasks directly at process equipment, in connection with decisions made by control room operators. Hence, good communication between the two must be maintained at an adequate level through the availability of a good and proper communicating system. A good communicating system must also related to point B3 reduce the noise level in the control room.

C. Workstation Design

Workstation is where the operators perform their tasks and is consisted of different HSI elements, such as displays and input devices. Types of workstation are i.e. sit-stand workstation, stand-up and sit-down consoles, vertical panels and desks. The design characteristics of workstation can affect reach, vision and comfort. Considerations correspond to the design of workstations must comprise the general configuration, labelling and signage of operating elements, and layout of panels and displays.

C1. Workstation configuration

The evaluation of workstation configuration comprises the unique consideration of the followings:

- Dimensioning, including workstation height, slope, angle and depth.
- Positioning, including placement of controls and distance from front edge of workstation
- Display location, positioning of displays on desks if not integrated mounted, location of displays to avoid glare and blinding
- Lateral spread of controls and displays
- Clearance for legs and feet
- Sitting and standing positioning relative to types of workstation

C2. Labelling and signage of controls & demarcation

Permanent labels are generally used to identify group of panels, controls and displays, individual items, instructions and control directions, whereas signs can be used to emphasize necessary instructions, warnings or forbiddance to perform certain actions. Demarcation lines are additionally used to identify workstation sections. The characteristics that need to be taken into consideration in evaluating the adequacy of labels, signs and demarcation lines are:

- Content
- Size
- Location
- Colourings and contrast
- Lettering
- Consistency and permanence

C3. Layout of panels and displays

In relation with point C1, the layout of panels and displays need to be extra evaluated in term of the placement of displays (vertical or horizontal placement of multiple displays), orientation relative to line of sight, viewing distance and the position of frequently and infrequently monitored display device.

D. Job Design

In maintaining the situational awareness during process monitoring, it is essential to design and allocate operators' responsibilities in such a way that guarantees a good proportion between performing process orientation, monitoring and evaluation, taking action and assessment of current situation. A proper job design must prevent and boredom to control room operators, and must on the other hand prevent work overloading and fatigue, both of which can lead to the reduction of situation awareness.

D1. Allocation of work

Works must be allocated to operators who meet necessary requirements demanded by the tasks to be completed. Several people may have limitations in performing certain works, so that they might require assistance from other co-workers. Hence, a consideration to always pair the operators must be taken into account in allocating the work, by combining necessary characteristics and limitations featured by each of them. Several points to be evaluated in term of work allocation may include:

- Whether the tasks assigned to the operator puts irrational demand that is beyond his/her capabilities.
- If the operators are assigned with task that is either too hard or too easy for him/her, whether the operator is provided with assistance from other co-workers or is responsible to assistance to other workers.
- Is the job assigned to the operators suitable for their qualifications, by not asking more than the operators may have been acknowledged with based on their working

experience, yet giving them the opportunity and space for learning more about the process and the work.

D2. Variation of work

Since the work in control room often deals with routines and monotonous activities that can cause boredom and reduce situational awareness, it is favourable to make the job a little more complex by putting more variation to it. This can include introducing more variety of tasks and to a certain possible extent, giving operators with more responsibilities in planning and execution of the work.

D3. Staffing

The attribute ‘staffing’ describes the availability of the minimum necessary number of experienced and apt operators present on a shift in order to complete the work successfully without putting too high load on each operator. By staffing, it is to be evaluated whether the distribution of age, level of experience, health condition or other physical and/or psychological limitations among the workers in one shift is in a good proportion that guarantees the availability of capable and fit operators to be present on each working shift. Some of the problems related to staffing would be:

- Qualified staff being too few on a shift or a particular job that requires skilled workers.
- Insufficient personnel leading to overloading and therefore stress.
- Excessive personnel leading to poor co-ordination and communication.

D4. Work scheduling & shifting plans

Work schedule and shifting plans are commonly a problem that occurs on every shift. There are many patterns of shift work rotation recognized these days, some of which are easier than others. However, the pros and cons between the patterns are still disputable and no conclusion can be made about which one suits best.

Hence, the evaluation can only first look at the satisfaction level among the workforce about the selected and implemented shift pattern, and whether the decision to enforce this certain pattern has taken their opinions into account. Additionally, the duration and frequency of rest breaks and how these are organised must also be taken into consideration in the evaluation.

D5. Proportion of manual/field work

Since in most of chemical process plants, there is still a considerably number of semi-automatic systems, the proportion between manual/field work and control room work needs to be maintained practical and realistic. During process monitoring operators are often required to perform direct manipulation at the process equipment while other operators monitor and manipulate the process from the control room. The amount of activities to be conducted directly on-site can have effect on many other aspects, such as the allocation of work, staffing and also communication system.

E. Operator Competence

Operator competence and cognitive ability is by far considered as one of the most important PIFs from operator's perspective. For many of them, regardless of all positive changes to the system, it is their own capability to comprehend the process condition and the system that counts in achieving the operation's goal. Attributes that contribute to operator competence are skill & knowledge, working experience, physical characteristics & fitness for duty, and adequate training and courses.

E1. Skill and knowledge

Skill describes the human ability to interpret information, for example to recall and carry out steps to perform tasks, technical reading and drawing skills. It also includes visual and hearing abilities. Since they are not inherent personal qualities, they can be obtained through training and experiences. Knowledge is all a person knows and understands in order to perform the task successfully. Knowledge is for example; understanding hazards, processes and operation procedures, equipment, and rules. Requirement of certain skill and knowledge depends on the kind of task to be performed by the operators. Many of the control room works require more understanding concerning the process and working experiences, without eliminating the need of good motoric and physical ability.

E2. Working experience

Experiences give the operator familiarity about the task, and in many cases play bigger role than trainings, especially in overcoming with abnormal situations. Due to the intensiveness of process knowledge required in performing process monitoring, tasks allocation needs to take into account the time an operator has spent at the corresponding plant. Lack of experiences can be compensated by good supervision and adequate communication with other co-workers.

E3. Operator physical characteristics and fitness

The work in control room requires particular reliability in aptitude and physical fitness for duty. Operators can easily lose sight of process status just after a slight reduction of concentration level due to tired eyes, drowsiness or uncomfortable feel after being in a sitting position for hours. In relation with the allocation of work in point D1, tasks must be allocated to operators by taking into account their physical limitations. In some cases it is desirable to issue some restrictions to performing particular tasks related to age or health condition.

E4. Training and courses

In analysing on-site tasks by means of the conventional PITOPA, the evaluation of training and courses is conducted implicitly through the evaluation of the level of skill and knowledge demanded by the task. Here, in analysing control room works, it is considered necessary to put training and courses and an extra point of evaluation and hence is separated from point E1. The evaluation comprises the actualization of training plans that include basic understandings about the operating system, including control and alarm system. Since computer and automation technology moves very rapidly, trainings to upgrade operators' skill and knowledge to be able to operate the more sophisticated operating elements need to be guaranteed, especially for the older ones.

F. Operator Supporting System

Operating supporting system in this analysis relates with all aspects that provide the operators with necessary information in evaluating and analysing process condition, and to correspondingly make decisions to overcoming with abnormalities. In other words, operator supporting system has the goal to provide the operators with necessary assistance during fault detection and diagnosis, and to direct them to finding proper solutions. The contributing attributes are the operating and working procedures, emergency safeguards and ERPs, and computerized operating procedure system.

F1. Operating and working procedures

Procedures refer to document system such as standard operating instructions, maintenance and emergency procedures. Operating procedures that are consisted of cautions, warnings and notes, and explain step-by-step instructions, should support the operator to perform their job safely. A good procedure is an important key to safe operation, quality assurance and environmental impact reduction. Many accidents happened because instructions were not followed, were missing or even incorrect. Since procedure is present to improve safety and reduce human error, it should be evaluated and improved in order to make sure that it is accurate and up-dated.

Procedures are aimed to support the operators with its user-friendliness, accurateness and conformation to appropriate standards, as well as its consistency in format and lay-out. Additionally, operating procedures must be maintained attainable for control room operators, by providing an adequate storage for such documents in the control room as discussed in point B1.

F2. Emergency safeguards and emergency response procedures (ERP)

In addition to the working procedures, operators also need to be provided with guidance concerning what they must do in facing emergency situations. There is a point where operators must terminate their effort to overcoming with upsets and for instance shut down the plant and walk away from the dangerous zone to protect their own life. This limit is however can be very vague, since operators' mind is generally set with the idea to always try to keep the process safe and continue running. It is difficult for them under such a stress to recognize whether an emergency has occurred. Hence, it is necessary that the system assists the operators in such situation to recognize the dangerousness of the condition by for instance automatically terminating all incoming instructions from operators. The system should in opposite give operators an instruction to perform emergency shut-down. To prepare the operators in facing such emergency situation, an emergency response procedures (ERP) needs to be made available and attainable in the control room.

F3. Computer-based operating procedure system (CBP)

Procedures are normally available in written form as commonly known as paper-based procedures (PBP). With the increasing implementation of computerized control systems and DCSs, and also the increasing requirement to promote operation safety, operating procedures are nowadays computerized, and widely known as the computer-based operating procedure (CBP), which is integrated into the control and monitoring system. CBP provides the operators with guidance in selecting proper actions during tasks completion. The purpose is to increase the likelihood that the goal of the tasks can be safely achieved by correctly presenting unambiguous and desired course/sequence of actions. However, CBP must always be good maintained and kept updated to achieving the purpose of its implementation.

The evaluation of CBP in this analysis must observe the relevance of the implementation for the completion of operators work and whether an updating plan is available to checking the actuality of the CBP.

Operator supporting systems are sometimes computerized (known as COSSs - computerized operator supporting systems). However, such system is not widely accepted yet, since an extra reliable configuration of COSS is essentially required. Every possible error and the remedial actions to it need to be identified, so that COSS can suggest proper and reliable recommendations to the operators during the remediation of abnormal condition. Operators' mind will be blocked with the suggestions offered by the system, and they will be no longer capable to automatically search for alternatives in solving the problems. Hence, if COSS is to be implemented at a plant, it must be made sure that the system is able to comprise every problem that might arise during any operating state.

G. Alarm System

An evaluation of alarm systems can be made in term of their physical and functional characteristics. The physical characteristics describe the relationship between alarm system and the other parts of the plant, including how alarm systems interact with operators. The functional characterization describes how the alarm system is used in plant operation.

G1. Number of alarms

The extreme large number of alarms is a common problem for control room operators. In a complex system, especially those that have been operating for many years, modifications, audits and reviews can add up the number of sensors and alarms from time to time. Without a good management of alarms, this increasing number can lead to over-alarming, flood, nuisance, and other typical alarm problems. An analysis of alarm logs often shows that the most frequent incoming or activated alarms are those that are in the reality irrelevant to operators' work. Hence, it is essential to limit the number of alarms, by re-identifying the real alarms and differentiate them from warnings and other annunciations. Moreover, it is also reasonable to group the alarms so that the presentation can be made based on this grouping to whom the alarms may concern. More about alarm presentation will be evaluated in point G4.

G2. Alarm prioritization

A good and proper prioritization of alarms holds one of the keys to a reliable process monitoring and controlling. Operators often feel overloaded by too many incoming alarms that are irrelevant, require no further actions from them or indicate non-dangerous situations. Improper alarm prioritization and their presentation to the operators can distract operators from the real important action at that particular moment. Such situation can force the operators to conduct erroneous actions that can ultimately result in a disaster. For this reason, the adequacy of alarm prioritization system implemented in the plant needs to be evaluated, starting with the basic rules how alarms are prioritised to how alarms with different priority are presented. The letter relate with point G4 discussed below.

G3. Available response time

In performing remedial actions, especially following a high-priority alarms, operators will require adequate time to process the information and make a proper decision correspondingly. The unavailability of sufficient time to respond will put more loads on them and hence cause stress that will disturb their information processing. Severe consequences may result from any incorrect decision taken during remedial actions and therefore this is to be strictly avoided. Hence, there must be an anticipation of the time a high-priority alarm should be presented to the operators, so that they can have adequate time to conduct corrective actions. The result coming from CROAA can help the identification of necessary time-span that must be made available for control room operators after acknowledging an alarm.

G4. Signalling and presentation

The presentation of alarms to the operators determines how fast and correctly they acknowledge and respond to incoming alarms. Alarms can be presented using visual or auditory components. The auditory components are designed to capture the operator's attention to a change in the plant, while the use of visual components guide attention to the appropriate alarm (by i.e. flashing) and provide detailed alarm information (i.e. alarm message). In some cases it can be desirable to combine visual and auditory components to display alarms.

Generally alarm display approaches can be characterized into three basic types; spatially dedicated, continuously visible (SCDV) alarm displays (e.g., tiles), alarm message lists (e.g., for temporary alarm displays) and integrated alarms into process displays. The presentation of alarms has to ensure that operators acknowledge especially the high-priority alarms in time, and to not letting the operators get distracted by the presentation of less important alarms. Several important characteristics of alarm presentation to be evaluated are:

- General characteristics (e.g., alarm graphics, selection of visual or auditory components, consistency of alarm coding)
- Display of high-priority alarms
- Display of alarm status (unacknowledged, acknowledged or cleared)
- Display of shared alarms (alarms that can result from more than one causes)
- Alarm messages/list

G5. Failures indication features

The failures indication features should let the operators know about any malfunction occurring in the alarm system. Whether a sensor is being repaired or software maintenance is being undertaken, operators need to be informed that certain functions of the system they are currently working with are not usable. Such indication will avoid misinterpretation and failures in taking further decisions.

G6. Maintenance

Maintenance of alarm systems must be well planned and frequently implemented to maintain the system reliability. Maintenance needs to take into account feed-backs from operators related to the user-friendliness of the system in operators; opinion. Related to point G5, undertaken maintenance and repairs must be informed to all operators to avoid them from gaining too much trust in a malfunctioning system.

H. Line Management

Line management is the implementation of organisational policies in the daily life of process operation. Hence, line management has a major impact on the conditions that influence error, since even if appropriate policies are enforced by the higher managerial level, these policies may be ineffective without the support of line management. There are several aspects correspond to the line management in maintaining effective operation and maintenance, such as a clear line of responsibility and supervision, communication and documentation, management of change, and the quality of the organisational and safety cultures themselves.

H1. Line of responsibility & supervision

It is needed to have a clear hierarchy of responsibilities in performing tasks. Lack of knowledge or experience concerning the task, or the need of any quick decision in emergency situations, can be compromised by the availability of adequate supervision. Supervision has the responsibility to allocate the activities for the whole team in order to achieve compliance using rules and procedures, monitoring the team performance, making decision whenever required, leading the team, facilitating workforce and maintaining good communication within the team, and ensuring and developing team work. Therefore, it is essential to have a clear path of responsibility and to have the right people with adequate knowledge and outstanding decision making ability placed on the supervising positions.

H2. Communication & documentation

Communication is the exchange of information between elements within the organisation. The management system is responsible for addressing the communication between the line personnel, staff personnel, supervisors and upper management. Maintaining good communication among co-workers and between different hierarchies is very essential in forming a good atmosphere at work. If this is achievable, workes's motivation and trust to the company can be increased, which will certainly lead to an improvement in their performance.

Documentation as one type of communication can refer to several meanings (ISO 14100):

1. Policy, objectives and targets set by management.

2. Description of scope of each management systems in the organisation.
3. Description of the main elements of management systems and their interaction and reference to related documents.
4. Documents and records required by regulations and by other subscribed requirements.
5. Documents including records determined by the organisation to be necessary to ensure the effecting planning, operation and control of processes, such as pipe and instrumentation diagrams (P&ID), flow diagrams, incident reports, procedures and other documents that can be found at the workplace.

Documentation should be considered as an essential activity since a good documentation can be used as learning material of failure or incorrect actions which were performed in the past and can help avoiding the same mistake from occurring again in the future. A record of how the recent process is performed should also be made, so that it can be used later as a consideration in taking a decision, anytime an improvement or enhancement of the plant is needed.

H3. Management of Change (MoC)

Changes made on any part of the plant or in the working procedure need to be analysed, planned, implemented, controlled and documented to avoid major hazards. The implications of restructuring the plant must be assessed to ensure that the plant personnel receive adequate resource to discharge their responsibilities. In dealing with control room works, the management of change plays a very big role, since any changes that are not well analysed and not adequately informed to the operators can result in disastrous events. Organisational changes include changes in role and responsibilities, organizational structure, staffing levels, staff disposition and others that might directly or indirectly affect the control hazards, such as changes in reporting relationships, objectives, resources, management system, available expertise for design, engineering support, procurement, etc.

H4. Organisational and safety culture

Organisational culture is the major component in determining safety performance and behaviour. It can be described as "a pattern of basic assumptions-invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration- that has worked well enough to be considered valid and therefore, to be taught to new members as the correct way to perceive, think and feel in relation to those problems" (Schein, 1985). Since line management is responsible for the implementation of organisational cultures and policies during plant operation, it is necessary to also evaluate how sufficient the organisational culture values process safety and human factors.